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The following report covers the time period October 2000–September 2001.

1. INTRODUCTION

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. Most research in astrophysics is carried out in two closely affiliated groups-the Institute of Geophysics and Planetary Physics and V-Division within the newly created Physics and Advanced Technologies (PAT) Directorate and, on a part-time basis, by about 22 other scientists who have additional responsibilities in large LLNL programs. There is a growing emphasis on laboratory astrophysics and high energy laser experiments, in particular, of relevance to astrophysics.

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. Until the end of August 2000 C. Alcock was the Director of the LLNL branch of IGPP, which is organized into two centers led by K. Cook (Astrophysics) and F. Ryerson (Geosciences). The current Director is K. Cook (Acting). The goals of the IGPP branch at LLNL (http://www.llnl.gov/urp/IGPP/) 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 $600,000 to UC campus faculty and staff members, enabling 23 collaborative projects.

The senior staff at the Astrophysics Research Center of IGPP consisted of K. Cook, C. Max and W. van Breugel. In addition, S. Gibbard, B. Macintosh and S. Marshall are staff members and there were several full-time postdoctoral fellows and researchers: S. Blais-Ouellette, G. Canalizo, A. Drake, W. de Vries, M. Hammergren, S. Keller, M. Lacy, S. Nikolaev, J. Patience, and P. Popowski. IGPP also hosts a large number of faculty and student visitors from the UC campuses. Among these, R. Becker, M. Gregg, A. Stanford, and B. Holden (UC Davis) spend a considerable portion of their time in the IGPP.

The Physics and Advanced Technologies Directorate 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 PAT in order to channel LLNL expertise in advanced instrumentation, as well as large-scale computing, into astrophysics applications. The Astrophysics Group, led by K. Cook, is presently developing astronomical instruments for X-ray spectroscopy, gamma-ray spectroscopy and imaging, gamma-ray burst follow-up, multi-object optical spectroscopy and imaging Fourier transform spectroscopy. A significant new program, led by D. Dearborn, to develop a 3-D stellar evolution code running on massively parallel computing systems has been started. The Astrophysics Group is also involved in a variety of astrophysical investigations including astronomical observations, theoretical modeling, and laboratory measurements. LLNL physicists C. Bennett, K. Cook, W. Craig, D. Dearborn, C. Mauche, H.-S. Park, R. Porrata, J. Wilson, E. Wishnow, R. Wurtz, and K. Ziock make up the core of the Astrophysics Group. A newly formed Advanced Detector Group in V-Division, lead by S. Labov, is actively developing new detector technologies for national security as well as astrophysical purposes. S. Labov and M. Frank are staff along with postdoctoral fellows and students J. Ullom, A. Loshak, M. van den Berg, D. Chow, M. Cunningham, O. Drury, L.J. Hiller and T. Niedermayr.

2. RESEARCH

2.1 MACHO Microlensing Survey

The Massive Compact Halo Objects (MACHO) Project is an experimental search for the dark matter, which makes up at least 90% of the mass of our Galaxy. It was initiated at LLNL and involves K. Cook, A. Drake, S. Keller, S. Marshall, C. Nelson, and P. Popowski (LLNL); C. Alcock and M. Lehner (UPenn), R. Allsman, T. Axelrod, K. Freeman, and B. Peterson (Mt. Stromlo Obs., Australia); C. Stubbs (CfPA and U/Washington); K. Griest and T. Vandehei (CfPA and UC San Diego); A. Becker (Lucent); D. Alves (STScI); D. Bennett (Notre Dame); M. Geha (UC Santa Cruz); D. Minniti (P. Universidad Católica, Chile); P. Quinn (European Southern Obs., Germany); W. Sutherland (VISTA); and D. Welch (McMaster University). In addition, G. Clayton (LSU) worked closely with the group analysing R Coronae Borealis stars in the MACHO database and G. Kovacs (Konkoly) worked witht the group analysing RR Lyrae.

The MACHO Project released a number of exciting analyses of data directed at the determination of the nature and masses of microlenses detected toward the LMC and Galactic bulge. Based on follow-up observations of LMC microlensing events with the Hubble Space Telescope (HST), the locations of the lensed stars were constrained. Most of them are located in the LMC, which suggests that most microlenses are in the Galactic halo. Although it is still not known what type of objects dominate the lensing toward the LMC, it was possible to directly detect one microlens. This lens belongs to the Galactic disk and is clearly seen in the HST images as a very red object close to the magnified star. Using constraints from the microlensing parallax fit and $(V-I)$ color from HST, it was concluded that this lens is a low-mass star.

On the opposite end of stellar mass spectrum, several events in the Galactic bulge were identified that are likely due to a population of Galactic black holes. Such a population of black holes and other massive stellar remnants would explain the long duration of many microlensing events toward the Galactic bulge which cannot be explained by normal stars based on the standard models of Galactic kinematics. The MACHO group has shown that when these long events are treated as anomalous objects associated with stellar remnants, the new lower microlensing optical depth toward the Galactic bulge becomes consistent with all other observational data and theoretical models.

The MACHO Project also publicly released the data constituting 8 years of observations of over 73 million stars in the LMC, SMC and galactic bulge. All data is now available using a searchable web interface and is provided either as image data or photometric lightcurves. The data is available at http://wwwmacho.anu.edu.au/Data/MachoData.html or http://wwwmacho.mcmaster.ca/Data/MachoData.html.

Archival MACHO data also yielded the exciting discovery of over 150 rapidly moving Milky Way stars towards the bulge and the LMC. These stars are located nearby in our Galaxy, but are moving in front of very dense regions of the sky. Thus their discovery will allow one to predict the occurrence of future microlensing events as the rapidly moving stars pass directly in front of the more distant stars of the LMC and bulge. Since the time and location of these events is predictable, valuable telescope time on a future instrument such as NASA's Space Interferometry Mission (SIM) may be scheduled, yielding much more precise measurements of microlensing then are currently achievable.

2.2 Kuiper Belt Objects

K. Cook, S. Marshall, and R. Porrata (LLNL) are collaborating with C. Alcock and M. Lehner (UPenn); I. de Pater, C. Liang, and J. Rice (UC Berkeley); J. Lissauer (NASA/Ames); T. Axelrod (MSSSO, Australia); S. King, T. Lee, A. Wang, S.-Y. Wang and C.-Y. Wen (Academia Sinica, Taiwan); W.-P. Chen, and W.-S. Tsay (National Central U., Taiwan); and Y.-I. Byun (Yonsei University, Korea) on the Taiwan-American Occultation Survey (TAOS). TAOS will perform a census of small objects (2-10 km) in the Kuiper Belt by searching for the brief occultations of stars by these objects. The occultations will be observed with four small telescopes to be located in the Yu Shan National Park in Taiwan. The first TAOS telescope was installed on Lulin peak in March 2000. The remaining telescopes are being integrated with the TAOS cameras and other elements of the control system at LLNL while development of power and network infrastructure continues at Lulin peak. The full four telescope system will be established at Lulin during 2002.

K. Cook and S. Marshall (LLNL) are collaborating with C. Alcock, D. Engel, J. Goldader, and M. Lehner; T. Axelrod, R. Moody, and B. Schmidt on a search for large TNOs with the Macho Telescope System at Mount Stromlo Observatory in Australia. The survey will cover over 2000 square degrees to a magnitude limit of at least 20 in the R band. The telescope system images 0.5 square degrees simultaneously in two filters. and has been in routine operation since May 2000. As of September 2001 have obtained 3 epoch observations of approximately 1700 square degrees near the ecliptic. The fully automated survey will continue into 2003. A moving object search is being carried out on the data set with several stages of candidate filtering, orbit fitting and possible follow-up imaging planned. Preliminary results will be presented in late 2001.

2.3 Gamma Ray Bursts

H. Park, S. Nikolaev (LLNL), G. Williams (U. Arizona) and S. Barthelmy (GSFC) are working on the Super-LOTIS/LOTIS telescopes that can promptly respond to gamma-ray burst triggers from the HETE2 satellite. Both systems can responded to HETE2 triggers within 100 sec and the limiting magnitude of Super-LOTIS is better than $R = 18.5$ to 20.0, depending on the integration times. Once reliable HETE2 GRB triggers are available, these systems will detect gamma-ray burst counterparts at very early times. This will provide measurements for understanding of gamma-ray burst progenitors. Park and collaborators are also working on automatic analysis software for LOTIS all sky monitoring data. This will produce a database for study of the transient sky.

K. Cook and B. Craig (LLNL), C. Alcock (UPenn), D. Bennett and S. Rhie (Notre Dame) and P. Meintjes (UOFS) are working to refurbish and instrument the Rockefeller Telescope of Boyden Observatory (University of the Orange Free State) for rapid response to gamma-ray bursts. This observatory will fill a needed latitude and longitude gap in the current GRB follow-up network.

J. Salmonson (LLNL) interpreted a recently discovered correlation between gamma-ray burst (GRB) luminosity and timescales as being due to variation in relativistic velocities among bursts (Salmonson 2000). It was also pointed out (Salmonson 2001) that if GRBs are narrow jets pointed very nearly directly at us, then this interpretation could explain the weak burst of April 25, 1998 and its association with supernova 1998bw as being a jet beamed at a relatively large angle of inclination with respect to us. Recent work with T. Galama (Cal Tech) has found a strong correlation between GRB timescales and the timescale in the afterglow lightcurve (Salmonson & Galama 2001). This work presents the closest yet known connection between the gamma-ray and afterglow phases of bursts and further supports the interpretation of the variation among gamma-ray bursts as being due to the variation of observed velocities.

J. Salmonson, J. Wilson (LLNL) and G. Mathews (Notre Dame U.) have continued work on neutron stars in a close binary system as a progenitor model for gamma-ray bursts (Salmonson, Wilson & Mathews 2001). They find that this model is satisfactory to explain many gamma-ray bursts. J. Salmonson and J. Wilson have worked out the neutrino pair annihilation rate into electron-positron pairs between heated neutron stars in a close binary system (Salmonson & Wilson 2001). These results are being used in current work by Salmonson and Wilson using 1-D and 3-D relativistic hydrodynamic codes to investigate neutron star binaries as progenitors for the class of ‘‘short’’ bursts (those that have duration of less than a second).

J. R. Wilson (LLNL) has implemented an axially symmetric general relativistic hydrodynamic computer program to study the head on collisions of neutron stars. Results so far indicate that the stars undergo compression long before colliding. When the metric is forced to be conformally flat and gravitational radiation is suppressed the compression is only slightly changed. The compression as a function of velocity is about the same for colliding stars and orbiting stars.

2.4 Hydrodynamics Simulations of Star Formation Processes

R. I. Klein (UC Berkeley and LLNL), T. Woods (LLNL) and C. McKee (UC Berkeley) studied the problem of interstellar cloud-cloud collisions with extreme high resolution local Adaptive Mesh Refinement (AMR) three dimensional Hydrodynamics. The problem is of great significance because of the possibility that such an interaction may trigger star formation in clouds, as well as provide a mechanism for developing complex structure in the interstellar medium. Previous work on this problem has been lacking in two fundamental ways; (1) inadequacy of the resolution necessary to capture the key hydrodynamic instabilities whose presence may destroy the clouds and (2) absence of any clear delineation of those conditions under which a gravitational collapse leading to star formation will occur during cloud-cloud collisions of initially stable clouds. The calculations have established two critical criteria that must be satisfied: (1) the Jeans criterion that demands that the Jean's length be well-resolved and (2) a minimal resolution of the cloud interaction region which addresses whether competition between gravitational collapse and pressure re-expansion of the compressed cloud will determine whether or not a collapse will occur. They obtained results for collisions for several different masses and a range of velocities to identify the parameter space for which a collision can lead to a triggered star formation. Key results are that for masses below a certain fraction of the Jeans mass there is a lower velocity limit to the collapse region; there is a minimum mass for a collapse to occur regardless of how fast or how slow clouds collide and there is a high velocity limit to the collapse region. A crucial finding of these models is that the parameter space for induced star formation by cloud collisions is surprisingly small.

R. I. Klein (UC Berkeley and LLNL) with R. Fisher (UC Berkeley) and C. McKee (UC Berkeley) continued their examination of the conditions under which binary and multiple stars may form out of turbulent molecular cloud cores using high resolution 3-D Adaptive Mesh Refinement hydrodynamics. This year they began the study of models that for the first time incorporated radiative transfer on an adaptive mesh into the simulations. They found that their previous models in which the initial cloud is assigned a turbulent velocity perturbation consistent with Larson's linewidth size relation is not turbulently mixed enough to drive binary star formation in molecular cloud cores that are marginally supersonic. They developed a self-consistent set of initial conditions that now allow for initial fluctuations in both the density and the velocity fields. They are investigating the onset of multiple star formation using such initial conditions with the promise of explaining the origin of binary stars.

R. I. Klein (UC Berkeley and LLNL) with C. McKee and graduate student R. Crockett (UC Berkeley) continued with developing a new 3D high order accurate MHD code with adaptive mesh refinement. They are employing Godunov hydrodynamic techniques to follow multi-dimensional shocks with great accuracy. They now have a working Godunov 2-D MHD and are extending this to 3D to investigate a series of MHD instabilities in the interstellar medium.

2.5 Stars and Stellar Populations

S. Keller (LLNL), G. Da Costa and M. Bessell (RSAA, Australian Nat. U.) presented results of a quantitative study of the degree of extension to the boundary of the classical convective core within intermediate-mass stars. The sample, drawn from young clusters in the Magellanic Clouds, affords a meaningful comparison with theoretical scenarios with varying degrees of convective core overshoot and binary star fraction. They conclude that the case of no convective core overshoot is excluded at a 2 σ level.

S. Keller (LLNL), in collaboration with E. Grebel (MPIA Heidelberg) presented a wide-field $UBVRI$ and Hα photometric study of the h and Chi Persei association. They find a common distance modulus and age for the twin nuclei of the association. The result affirms the binary nature of the association. The study forms a spatially and photometrically complete survey for Be stars. Comparison of the Be star population within the association is made to that found in similar cluster populations within the Magellanic Clouds. Keller *et al.* propose a scenario of evolutionary enhancement of the Be phenomenon to account for the peak in Be fraction towards the terminus of the main sequence.

S. Keller (LLNL) in collaboration with A. Korn (Univ. Sternw. Muenchen) implement updated NLTE model atoms to study the abundances of four main-sequence B stars in the young cluster NGC 2004 in the Large Magellanic Cloud. This study finds nitrogen abundances comparable to those measured in LMC H II regions ([N/H] ~ -1) finally settling the question of the pristine LMC nitrogen abundance in favour of the low nebular value. Thus, the Magellanic Clouds turn out to be nitrogen-poor by a factor of 3 when compared to stars of the same metallicity in the Galactic thin disk ($[N/Fe]_{LMC} \sim -0.6$ vs $[N/Fe]_{Gal.disk} \sim -0.1$). This finding is yet another example which indicates that the chemical evolution of the MCs differs significantly from that of the Galaxy.

C. Nelson and K. Cook (LLNL) are collaborating with J. Mould (NOAO), T. Axelrod, G. Da Costa, K. Freeman (ANU) and C. Alcock (UPenn) on a survey to detect halo white dwarfs. This is a complementary effort to the MACHO Project as ancient halo white dwarfs are a favourite MACHO candidate. The survey searches for halo white dwarfs as high proper motion objects in a second epoch HST image of a strip of the sky at high Galactic latitude, first imaged in 1994 and commonly referred to as the 'Groth Strip'. The majority of the data was taken the past year and five white dwarf candidates were detected. Simulations are currently in progres to determine the relative contribution to our sample from the Galactic disk and the Galactic halo. No evidence is found that the sample suggests a significant population of ancient halo white dwarfs, which in turn implies that white dwarfs are not a significant contributor to Galactic halo dark matter.

S. Nikolaev (LLNL) studied the stellar populations and geometry of the Large Magellanic Cloud, as a part of his Ph.D Thesis at University of Massachusetts, Amherst (advisor: Prof. M. Weinberg). Stellar populations were identified based on Near-Infrared color-magnitude diagram from Two Micron All Sky Survey (2MASS). One of the results from this study has been identification of a significant ($\sim 10^4$) population of long-period variables (LPV) in the LMC, which can be used as standard candles (in a narrow $J-K_s$ color range). A closer look at the distribution of carbon-rich LPVs in the LMC provided marginal evidence for structural component of the LMC extended along the line of sight.

2.6 3D Simulations of Stellar Structure and Evolution

Stars provide the fundamental quantitative units for measuring the universe. They are the foundation for determining distances and ages, and factories driving chemical evolution. Stars continue to be used as physics laboratories for constraining the properties of fundamental particles (cross sections, masses, ...), as well as hot plasmas (opacity, Equation of State (EOS), ...).

Current practices in stellar evolution employ one dimensional calculations that quantitatively apply only to a minority of the observed stars (single non-rotating stars, or well-detached binaries). Even in these systems, astrophysicists are dependent on models of complex three dimensional (3D) processes like convection. At LLNL, Dearborn, Eggleton and colleagues are leveraging research from across the lab (Defence and Nuclear Technologies, Physics, Center for Applied Scientific Computing) to develop a stellar evolution code that operates on massively parallel machines with the best available physical data (Opacities, EOS, etc.) as well as new algorithms.

In September of 2000, they had successfully executed a three dimensional hydrodynamic simulation of a star on the TC2K computer system at LLNL. Modeling a whole star in 3D was a significant step, but it was a single processor run, with partial physics, and an under-resolved (400k zone) mesh. This progress enabled subsequent work in which different mesh constructs were studied, the accuracy of the 3D models were tested and improved, and physics optimization was begun.

The computer code, 'Djehuty', now has an accurate equation of state, astrophysical opacities for use with its radiative diffusion transport package, and a nuclear reaction-network for hydrogen, helium, and carbon burning. The gravity implementation is currently complete only for spherical stars, but is adequate for a first major science study of convective cores. Large (>50 million zone) meshes were needed for realistic stellar modeling, and the operation is being moved from a parallel to a massively parallel environment. 3D stellar models have now been decomposed and run in parallel operations on up to 256 processors.

With the basic elements of Djehuty functional, a number of extended parallel runs have been made to address a long standing, well characterized discrepancy between one dimensional stellar models and observed stars. This is an important validation step for presenting Djehuty to the astrophysical community. It has also allowed to find and fix a number of code problems. Work on a generalized gravity algorithm identified a problem in the solver package for radiative diffusion. A major upgrade of that package is now complete, and running of the necessary test cases has been resumed.

Documenting the code for a publication has begun, and preliminary results have been presented at a number of conferences. Algorithm development is continued for both the physical processes and the data exploration necessary for studying rapidly rotating stars and binaries.

2.7 Stellar High Energy Astrophysics

H. Dalhed and J.R. Wilson (LLNL) have developed a table equation of state to use in the Maye-Wilson supernova computer model. Improvements have been made in the equation of state and in the neutrino diffusion model. The result is that at late times the entropy peaks at 550 which effect should improve the r-process numbers.

D. Liedahl (LLNL), in collaboration M. Jimenez-Garate, C. Hailey (Columbia Univ.), and J. Raymond (CfA), modeled the X-rays reprocessed by accretion disks in low-mass X-ray binary systems with a neutron star primary (Jimenez-Garate *et al.* 2001). An atmosphere, or the intermediate region between the optically thick disk and a Compton-heated corona, is photoionized by the neutron star continuum. X-ray lines from the recombination of electrons with ions dominate the atmosphere emission and should be observable with the Chandra and XMM-Newton high-resolution spectrometers. The self-consistent disk geometry agrees well with optical observations of these systems, with the atmosphere shielding the companion from the neutron star. At a critical depth range, the disk gas has one thermally unstable and two stable solutions. A clear difference between the model spectra exists between evaporating and condensing disk atmospheres. This difference should be observable in high-inclination X-ray binaries, or whenever absorbing material blocks the central continuum but not the extended disk emission.

D. Liedahl (LLNL), in collaboration with P. Wojdowski (LLNL), M. Jimenez-Garate, and M. Sako (Columbia Univ.) reviewed ongoing efforts to interpret X-ray line spectra in the context of large-scale "global" models of X-ray binaries, including models of line production in the X-ray photoionized stellar winds of high-mass X-ray binaries, as well as irradiated accretion disks in low-mass X-ray binaries.

D. Liedahl (LLNL), in collaboration with R. Smith, N. Brickhouse, and J. Raymomd (CfA), introduced a new plasma emission code, the Astrophysical Plasma Emission Code (APEC), which uses atomic data from the companion Astrophysical Plasma Emission Database (APED) to calculate spectral models for hot collisionally-ionized plasmas. APED contains the requisite atomic data, such as collisional and radiative rates, photoionization cross- sections, dielectronic satellite lines, and line wavelengths. APEC results were compared to other plasma codes for hydrogen- and helium-like line ratio diagnostics. It was found that dielectronic recombination onto hydrogen-like ions that result in excitation of high- lying shells in helium-like ions must be accounted for in order to accurately predict helium-like line ratios involving transitions to ground from the n=2 shell.

D. Liedahl (LLNL), in collaboration with J. Cottam, M. Sako, S. Kahn, and F. Paerels (Columbia Univ.), presented a preliminary analysis of the X-ray spectrum of the accretion disk corona source 4U1822-37, obtained with the High Energy Transmission Grating Spectrometer aboard the Chandra Observatory. Emission lines from photoionized iron, silicon, magnesium, neon, and oxygen, as well as a bright iron fluorescence line were found. Orbital phase-resolved spectroscopy suggests that the recombination emission originates in an X-ray illuminated bulge located at the predicted point of impact between the disk and the accretion stream. The fluorescence emission appears to originate in an extended region of the disk that is illuminated by X rays scattered from the corona.

C. Mauche, D. Liedahl, and K. Fournier showed that the Fe XVII I(17.10 Å)/I(17.05 Å) line ratio observed in the Chandra High Energy Transmission Grating (HETG) spectrum of the intermediate polar EX Hydrae is significantly smaller than that observed in the Sun or other late-type stars. Using the Livermore X-ray Spectral Synthesizer, which calculates spectral models of highly charged ions based on HULLAC atomic data, they found that the observed I(17.10 Å)/I(17.05 Å) line ratio can be explained if the plasma density $n_e > 3\times10^{14}$ cm^{-3}. However, if photoexcitation is included in the level-population kinetics, the line ratio can be explained for any density if the photoexcitation temperature $T_{bb} > 55$ kK. For photoexcitation to dominate the Fe XVII level-population kinetics, the relative size of the hotspot on the white dwarf surface must be less than 2%. This constraint and the observed X-ray flux requires a density $n_e > 2\times10^{14}$ cm^{-3} for the post-shock flow. Either way, then, the Chandra HETG spectrum of EX Hya requires a plasma density which is orders of magnitude greater than that observed in the Sun or other late-type stars.

C. Mauche, J. Mattei (AAVSO), and F. Bateson (VSS/RASNZ) combined AAVSO and VSS/RASNZ optical and Extreme Ultraviolet Explorer EUV light curves of dwarf novae in outburst to place constraints on the nature of dwarf nova outbursts. From the observed optical-EUV time delays of 0.75-1.5 days for VW Hyi, U Gem, and SS Cyg, they showed that the propagation velocity of the dwarf nova instability heating wave is ~ 3 km s^{-1}. That result is consistent with the expected propagation velocity $v=\alpha c_s$ if the viscosity parameter $\alpha\sim0.2$ and the sound speed $c_s = 10(T/10^4K)^{1/2} \sim 15$ km s^{-1}.

P. Wheatley (Univ. of Leicester), E. Kuulkers (SRON), J. Drake (SAO), J. Kaastra (SRON), C. Mauche, S. Starrfield (Arizona State), and R. Wagner (Univ. of Arizona) observed the cataclysmic variable WZ Sge in outburst on 2001 July 27 with the Chandra Low Energy Transmission Grating Spectrometer (LETGS) and found that the dispersed spectrum extends from 20 to 175 Å . Longward of 65 Å , the spectrum is dominated by a forest of broad (FWHM = 800-1200 km s^{-1}) emission lines of such species as O V-VI, Ne V-VIII, Mg V-VII, and Fe VII-IX. Shortward of 65 Å weaker lines of highly ionized ions were observed, with O VIII (18.9 Å) the strongest. The long-wavelength LETG spectrum is very similar to the EUVE spectrum of OY Car in superoutburst and appears to be formed by the same mechanism – scattering of boundary-layer radiation in the system's accretion-disk wind. A second Chandra observation of WZ Sge was made with the ACIS-S CCD detector on 2000 July 29. The source was detected at X-ray energies up to 7 keV, and was found to be dominated by strong emission lines. Most features can be accounted for with a multi-temperature thermal plasma model, with the exception of an anomalously strong emission line at 2.4 keV, possibly due to S XV.

2.8 Galaxies and Clusters of Galaxies

M. Gregg (UC Davis and LLNL), M. Drinkwater (UNSW), M. Hilker (ESO), S. Phillipps (U. Bristol), R. Smith (U. Wales) and W. Couch (U. Sydney), are pursuing follow-up studies of the enigmatic "ultra-compact dwarf" galaxies that they recently discovered in the Fornax cluster. Essentially unresolved in ground based imaging, the extremely compact Fornax cluster members, five known at present, have $-13 < M_B < -11$, $\sim 1-2$ magnitudes brighter than the largest globular clusters in NGC 1399. These unusually compact objects might be the surviving nuclei of stripped dwarf ellipticals or intermediate objects between galaxies and globular star clusters, or perhaps even the densest star clusters formed from the disruption of larger star forming galaxies infalling into the Fornax cluster at some long past epoch. Using imaging with STIS on the Hubble Space Telescope and VLT echelle spectroscopy, the group has determined core radii and velocity dispersions for these tiny objects, yielding masses and mass-to-light ratios. Their luminosity profiles and velocity dispersions are consistent with their being the stripped nuclei of dwarf ellipticals, although their low mass-to-light ratios suggest that they may harbor young or intermediate age populations.

D. Proctor (LLNL) continued to work on the automatic classification of bent-double radio galaxies from the FIRST survey. Such sources may be used as tracers of clusters of galaxies (Blanton, *et al.*, 2000). Pattern recognition techniques were applied to generate a well-defined sample with approximate posterior class probabilities. A paper has been submitted discussing automated selection of three-component bent doubles (Proctor, 2001). A paper on the classification two-component bent doubles is in preparation.

S. A. Stanford and graduate student J. Whalen (UC Davis and LLNL) continued the search for high redshift galaxy clusters using bent double radio sources selected from the FIRST survey. J. Whalen has begun using the data available from the Sloan Digital Sky Survey to search for evidence of clusters around bent doubles. The available photometry is being searched for both galaxy overdensities in 2-D spatial projections, and for concentrations in redshift space by estimating photometric redshifts for detected galaxies.

S. A. Stanford and B. Holden (UC Davis and LLNL) obtained deep X-ray images of three high redshift galaxy clusters using the Chandra OBservatory. These data were analyzed to determine the temperature and morphologies of the hot intracluster gas. All three of the clusters have temperatures and bolometric X-ray luminosities which agree with the low-redshift relation. The results were presented by Holden at a galaxy clusters conference in Italy. These clusters were found in the final identification phase of the Rosat Deep Cluster Survey which has been led by P. Rosati (ESO), in collaboration with Stanford, Holden (UC Davis and LLNL), P. Eisenhardt (JPL), S. Borgani (Trieste), G. Squires (Caltech) and P. Tozzi (Trieste).

S. A. Stanford (UC Davis and LLNL), P. van Dokkum (Caltech), and B. Holden (UC Davis and LLNL) investigated the galaxy population of the high redshift cluster RX0848 +4453 at z=1.27 using NICMOS and WFPC2 images, and deep Keck spectroscopy. They found that about half of the member galaxies are early-type which is a significantly lower fraction than is seen in low-redshift clusters. The deep Keck spectra were used to obtain velocity dispersions and show that at least some of the early-type galaxies in the z=1.27 cluster follow an evolved version of the Fundamental Plane.

2.9 Active Galaxies and Quasars

R. Becker (UC Davis and LLNL) continued his work with extragalactic surveys, including both the FIRST survey and the Sloan Digital Sky Survey. The FIRST survey continues to expand its sky coverage. In the Spring, 2001 another block of observing time on the VLA was allocated which was used to extend the survey in the NGP south to -10 degrees declination. Comparisons between FIRST and 2MASS have been successful at finding extremely red quasars, two of which were gravitationally lensed. The FIRST team also published the third release of the FIRST Bright Quasar Survey which better detailed the dependence of the frequency of Broad Absorption Lines (BALs) on radio brightness. Becker is also part of the team of SDSS scientists searching for ever more distant quasars. This year saw the record pushed up to z=6.28. Even more importantly, the spectrum of the quasar shows an unambiguous Gunn-Peterson trough indicating the transition from a neutral universe to a ionized universe at a redshift of 6.

R. Becker (UC Davis and LLNL), D. Helfand (Columbia Univ.), and R. White (STScI) also started a new radio survey of the Galactic plane using the VLA in three configurations (B, C, & D). The pilot covered 13 degree strip in Galactic longitude (19 to 32 degrees) with a width of 1 degree (Becker *et al.* 2000). The intention is to broaden the coverage in the coming year.

M. Brotherton (NOAO), M. Grabelsky (Rice Univ.), G. Canalizo, and W. van Breugel (LLNL) continued the study of the z=0.6344 poststarburst quasar UN J1025-0040 using HST WFPC2 images. This object harbors an AGN and a 400-Myr-old nuclear starburst of similar bolometric luminosities. The new HST images show that there is an even younger, unresolved nuclear starburst (40 Myr or younger) that may be associated with the trigger of the current quasar activity, and which complicates the already complex interaction and starburst history of this system.

G. Canalizo and W. van Breugel (LLNL) are conducting a spectroscopic survey to identify new candidate ultraluminous infrared galaxies (ULIGs) from a radio-selected FIR sample resulting from correlating the FIRST catalog and the IRAS Faint Source Catalog. This selection method is not biased towards the presence of AGN, and is efficient at selecting objects at relatively higher redshifts. In addition, the objects in the sample are suitable for adaptive optics (AO) observations as they have nearby bright stars; a follow up AO-imaging survey is under way to study in detail the morphology of these galaxies and of any possible active nuclei and/or starbursts in the galaxy.

G. Canalizo (LLNL) and A. Stockton (U. Hawaii) conducted a deep spectroscopic and imaging study of the host galaxies of the only four low-ionization broad absorption line (BAL) QSOs that are currently known at $z<0.4$, and found that all four objects reside in dusty, starburst or post-starburst, merging systems. The starburst ages derived from modeling the stellar populations are in every case a few hundred million years or younger. There is strong evidence that the ongoing mergers triggered both the starbursts and the nuclear activity, thus indicating that the QSOs have been recently triggered or rejuvenated. The low-ionization BAL phenomenon then appears to be directly related to young systems, and it may represent a short-lived stage in the early life of a large fraction of QSOs.

M. D. Gregg, R. Becker, M. Lacy (UC Davis and LLNL), R. White (STScI) and D. Helfand and E. Glikman (Columbia Univ.), have been searching for examples of extremely red quasars by matching sources in the FIRST survey to the infrared point source catalog recently released by the Two Micron All-Sky Survey (2MASS) team. The early results have turned up two extraordinarily red quasars. FIRST J013435.7-093102 is a 1 Jy source at $z=2.216$ and has $B-K\gtrsim 10$, while FIRST J073820.1+275045 is a 2.5 mJy radio source at z=1.985 with $B-K\approx 8.4$. Having intrinsic narrow line aborption and high polarization, FIRST J073820.1+275045 appears to be reddened by dust in its local environment and is one of the few low radio-luminosity, highly dust-reddened quasars known. FIRST J073820.1+275045 and analogous objects now emerging from X-ray surveys suggests the existence of a radio-quiet red quasar population. Such objects will be entirely missed by standard radio or optical quasar surveys. FIRST J013435.7-093102 is gravitationally lensed, raising the possibility that it is reddened by a very dusty intervening galaxy. Extinction by dust in the intervening galaxy can effectively cancel the optical brightness magnification by gravitational lensing, making it difficult to detect such examples of lensed quasars, suggesting that a population of optically faint, gravitationally lensed quasars may exist.

M. Lacy, S. Laurent-Muehleisen (UC Davis and LLNL), S. Ridgway (Johns Hopkins Univ.), R. Becker (UC Davis and LLNL) and R. White (STScI) have used quasars from the First Bright Quasar Survey to investigate the relationship between the radio luminosity of a quasar and the mass of its black hole, finding a good correlation between the two, and also finding a dependence of radio luminosity on the rate of accretion of gas by the black hole.

M. Lacy (UC Davis and LLNL) has continued to collaborate with M. Wold, a PhD student at Stockholm Observatory, investigating the Mpc-scale environments of powerful quasars and other AGN. They find that both radio-loud and radio-quiet quasars can be found in environments ranging from field-like to rich clusters, but that, on average, AGN are found in richer environments than field galaxies. They also conducted the first weak-lensing analysis of clusters around AGN, finding that clusters associated with AGN can have deep potential wells, contrary to some suggestions that clusters associated with AGN may be dynamically young. There is also tentative evidence that clusters selected through the presence of an AGN may have higher mass–to–light ratios than those selected purely on the basis of a high baryonic content (e.g. optical or X-ray selection).

D. Liedahl (LLNL), in collaboration with M. Sako, S. Kahn, E. Behar (Columbia Univ.), J. Kaastra, A. Brinkman (SRON), Th. Boller (MPI), E. Puchnarewicz, R. Starling (MSSL), J. Clavel, and M. Santos-Lleo (ESA), observed IRAS 13349+2438, a luminous infrared-loud quasar, with the XMM- Newton observatory as part of the Performance Verification Program. The spectrum obtained by the Reflection Grating Spectrometer exhibits broad (1400 km/s) absorption lines from highly ionized species, including H-like and He-like C, N, O, and Ne, as well as several Fe L-shell features. In a separate study they also reported the first astrophysical detection of a broad absorption feature near 16Å , identified as an unresolved transition array of 2p-3d inner-shell absorption by Fe M-shell ions. They demonstrate that the spectrum indicates absorption from at least two distinct regions, one of which is tentatively associated with the medium that produces the optical/UV reddening.

C. De Breuck (IAP, and previous LLNL student guest), in collaboration with W. van Breugel, W. de Vries (LLNL), A. Stanford (UC Davis and LLNL), D. Stern (JPL, and previous LLNL student guest), and Leiden Observatory colleagues H. Rottgering, G. Miley, J. Kurk and R. Overzier, obtained optical spectroscopy of 62 objects selected from several samples of ultra-steep-spectrum radio sources. Forty-six of these are from a large catalog of 669 'ultra–steep spectrum' (USS) sources with radio spectral indices $\alpha < -1.30$ ($S_\nu \sim \nu^\alpha$) and faint optical and near-IR identifications. Most galalaxies are identified as narrow-lined radio galaxies with redshifts ranging from z=0.25 to z=5.19. Ten objects are at $z > 3$, nearly doubling the number of such sources known to date. Four of the USS radio sources are identified with quasars, of which at least three have very red spectral energy distributions. The source TN J0936-2242 is identified with an extremely red object (ERO, $R - K > 5$) at z=1.479. Five sources show continuum emission, but fail to show any clear emission or absorption features, despite integrations of 1 hr with the Keck telescope. These objects could be (1) radio galaxies with faint emission lines in the ''redshift desert'' at $1.5 < z < 2.3$, (2) radio galaxies with an obscured active galactic nucleus, which are dominated by a stellar continuum observed with an insufficient signal-to-noise ratio, or (3) pulsars. Three radio sources identified with faint objects in the K-band images remain undetected in 50-90 minute spectroscopic integrations with the Keck telescope, and are possible $z > 7$ candidates.

C. De Breuck (IAP, and previous LLNL student guest), W. van Breugel (LLNL) and Leiden Observatory colleagues (H. Rottgering, G.K. Miley and P. Best) compiled a sample of 165 radio galaxies from the literature to study the properties of the extended emission line regions and their interaction with the radio source over a large range of redshift $0 < z < 5.2$. Using various radio and optical spectroscopic parameters they find the following significant correlations: (i) Lyman-α asymmetry with radio size and redshift, (ii) line luminosity with radio power, (iii) line luminosities of Lyman-α, CIV, HeII and CIII with each other, and (iv) the equivalent widths of Lyman-α, CIV, HeII and CIII with each other. The correlation between redshift and absorption line asymmetry is interpreted as an increase in the amount of HI around radio galaxies at $z > 3$. The almost exclusive occurrence of HI absorption in small radio sources could indicate a denser surrounding medium or a region with a large column density. The other correlations (ii to iv) provide evidence for a common energy source for the radio power and total emission line luminosity, as found in flux density-limited samples of radio sources. Using emission-line ratio's to examine the ionization mechanism in the radio galaxies it was found that both AGN photo-ionization and shock ionization must be present. The latter is indicated by the CII/CIII ratio's, which are closer to high velocity shock model predictions than to the line ratio's expected for pure AGN photoionization. It was found that shock dominated ionization seems to occur mostly in the smallest radio sources.

W. van Breugel (LLNL), in collaboration with D. Stern and P. Eisenhardt (Caltech/IPAC), H. Spinrad and S. Dawson (UC Berkeley), A. Dey (NOAO), W. De Vries (LLNL) and S.A. Stanford (UC Davis and LLNL) used deep near–IR and optical photometry with the Keck telescopes to show that the claimed z = 6.68 galaxy STIS 123627+621755 is no longer the most distant galaxy. Instead they find that the object is most likely a low luminosity dwarf galaxy like the Small Magellanic Cloud (M(B) = -17) at a redshift z = 1.51.

3. ADAPTIVE OPTICS

3.1 Systems Development

The Adaptive Optics (AO) system on the 10-m W.M. Keck II telescope, jointly constructed by LLNL and the California Association for Research in Astronomy, achieved first light in February 1999 and entered general scientific use in late 1999-early 2000. AO uses deformable mirrors to actively control the wavefront of incoming light and correct for atmospheric turbulence. The Keck AO system routinely achieves resolutions of 0.04 arcsconds in H-band, the highest-resolution infrared imaging system in astronomical use. The LLNL participation in the Keck AO effort is led by S. Olivier and C. Max.

The LLNL AO team, led by D. Gavel, with D. Pennington, B. Bauman, J. Patience, B. Macintosh and C. Max (LLNL), supported the world's only operational sodium laser guide star (LGS) adaptive optics (AO) system on the 3-m Shane Telescope at Lick Observatory. The system routinely achieves 2 micron Strehl ratios of 0.4-0.6 requiring only a $R < 17$ tip-tilt star within 60 arcsec. System reliability has been upgraded to the point where it has been made available for shared-risk scientific observations, beginning in August 2001. Meanwhile, the LLNL-built laser for the Keck AO system LGS mode was installed on the W.M. Keck II telescope in fall 2001.

As part of the NSF-funded Center for Adaptive Optics LLNL began research in the area of next-generation high-contrast adaptive optics systems. B. Macintosh gave an invited talk at the June 2001 AAS Special Session on high-contrast imaging, and Macintosh and J. Patience presented papers at the August 2001 SPIE annual meeting. S. Olivier (LLNL) is leading the Center's project to develop micro-electro-mechanical technology for next-generation AO.

3.2 Solar System

C. Max, B. Macintosh, S. Gibbard and D. Gavel (LLNL), along with UC Berkeley collaborators I. de Pater, and graduate students H. Roe, and S. Martin (UC Berkeley), have been observing solar system objects at very high spatial resolution using AO at the 10-meter W.M. Keck Telescope. This project focuses on observations and modeling of Saturn's largest moon Titan and the gas giant planets Uranus and Neptune. During February 2001 excellent images of Titan were obtained, including H-band spatially-resolved spectra using the Keck Telescope's NIRSPEC spectrograph behind the adaptive optics system. Spectacular new images of Neptune have revealed narrow zonal bands at 3-4 degree latitude spacings within bright regions and near the equator. The morphology of these infrared-bright features suggests wave or vortex structure. Analysis of images of the planet Uranus and its ring system obtained in June and August 2000 is ongoing. Inside of the Epsilon ring at least three more (individually slightly resolved) rings are visible: from the outside inwards these are: 1) combined Delta, Gamma, Eta rings, 2) combined Beta,Alpha rings, and 3) combined 4,5,6 rings. Modeling efforts have focused on model-based deconvolution of the ring images in order to determine the reflectivity of the individual rings.

3.3 Extrasolar Planets

AO on 8-10 m telescopes is capable of directly detecting the infrared emission from young extrasolar planets. Keck AO is capable of detecting objects at contrast ratios of 10^6, sufficient to see a 1 Jupiter-mass planet in a 50 AU orbit around a star in the TW Hydra association. B. Macintosh (LLNL), B. Zuckerman and E. Becklin (UC Los Angeles) are carrying out a large-scale search for planetary companions to young stars in nearby associations, as well as studying the binary fraction among these young stars.

3.4 Active Galaxies and Starburst Systems

C. Max and G. Canalizo (LLNL), together with D. Whysong and R. Antonucci (UC Santa Barbara), continued their program of adaptive optics observations of nearby active galactic nuclei. The goal of this project is to observe a sample of 25 - 30 AGNs, to determine whether inner spirals, bars, or other mechanisms are responsible for the inward transport of matter from radii of 100 kpc to the 10's of parsec region where the gravitational field of the black hole is dominant. To date in this program, the central regions of 11 AGNs have been imaged with adaptive optics at the Keck and Lick Observatories. Spectroscopic studies of a few of the most interesting AGNs are under way.

W. van Breugel and W. de Vries (LLNL), in collaboration with A. Quirrenbach, J. E. Roberts and K. Fidkowski (UC San Diego) used the Keck Observatory AO system to obtain high resolution images of the $z = 1.786$ radio galaxy 3C 294 in the H and K' infrared bands. The infrared emission of 3C 294 is dominated by two distinct components separated by ~ 1 arcsec (9 kpc). The eastern knot contains an unresolved core that contributes 4% of the K'-band light, which is identified with the active nucleus. The western component is about 2.5 times brighter. The most plausible interpretation of the near-infrared morphology is an ongoing merger event, with the active nucleus located in the less massive of the two galaxies.

4. INSTRUMENTATION

V-Division has been developing advanced imaging Fourier transform spectrometers (IFTS) for ground and space-based astronomy. C. Bennett, K. Cook, E. Wishnow, and R. Wurtz (LLNL) have participated in design studies and a prototype instrument development program. Collaborators include J. Graham (UC Berkeley), C. Stubbs (U Washington), S. Blais-Ouellette (LLNL and U Montreal), F. Grandmont (Laval University/ABB Bomem), W. van Breugel (LLNL), and M. Abrams (ITT).

An IFTS is an instrument that counts ''all the photons all the time,'' and obtains ''a spectrum for every pixel'' in the imaged field. An IFTS is the premier instrument for observing a field that is crowded with possible objects of interest, or contains an extended object whose constituent parts possess spectra with features at unknown wavelengths, or possess several spectral features across a passband. As compared with a grating spectrometer, the free spectral range is only limited by the passband of the input and output optics, and the spectral resolution can be tuned to the scientific requirements of the observation. In contrast to existing non-imaging FTS systems, IFTS are intended for low- to-medium spectral resolution simultaneous observations of faint objects. This project is developing both visible and mid-IR capability.

The present IFTS design is potentially suitable for space-based instruments. The interferometer was built by Bomem, Inc. for CSA as part of the IFIRS pre-phase-A study for NGST instrumentation. LLNL designed and assembled visible optics and camera system and integrated the instrument into a package comparable in size and weight to Cassegrain instruments for 3-meter class telescopes. LLNL then made extensive modifications to the interferometer so that it could be operated under adverse mountaintop conditions.

Commissioning of the instrument was completed at the 3.5-meter Apache Point Observatory in June 2001. Science observations will proceed during the coming year. Initial investigations will include R 100 studies of galaxy clusters and R 10,000 studies of galactic and extragalactic nebular regions.

The IFTS group is conducting research into detailed technologies necessary to develop this instrument in the areas of sub-micron scanning mirror servo control systems, beamsplitter designs and optical coatings, integration of camera systems and data handling, ‘‘quick-look’’ data inspection software, and hyperspectral datacube reduction techniques. The novelty of the kinds of observations advocated by this instrument concept has led to investigations of further applications. Among these are the use of IFTS instruments on board future planetary probes to Mars and/or the outer planets.

J. Ullom, S. Labov, M. Frank, A. Loshak, M. van den Berg, T. Miyazaki, A. Clark, S. Friedrich (LBNL and LLNL) D. Chow, M. Cunningham, O. Drury, L.J. Hiller (UC Davis and LLNL) T. Niedermayr (Univ. P. & M. Currie and LLNL) are developing cryogenic 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, the cryogenic X-ray detectors can provide high spectral resolution with high efficiency across a wide energy range. It should also be possible to construct cryogenic imaging detectors to provide spectral imaging of extended objects such as supernova remnants and hot gas in clusters of galaxies. Two types of detectors are currently under development. The microcalorimeter uses a sensitive thermometer to measure the temperature rise which occurs after an X-ray is absorbed in the detector. Microcalorimeters using superconducting transition-edge sensors are being developed at LLNL in support of the proposed ’Constellation-X’ NASA mission. An array of small microcalorimeters is also being developed to search for reflected infrared light from planets using speckle techniques. The superconducting tunnel junction (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 24 eV FWHM (6 keV), and less than 10 eV FWHM (below 1 keV) have been measured with STJ detectors at LLNL. These detectors have been demonstrated to operate at more than 20,000 counts/sec. In principle, resolving powers as high as 1000 may be obtainable in the X- ray band.

E. Wishnow (LLNL) is the Principal Investigator, and R. Wurtz and K. Cook (LLNL) are collaborators on the Long Wavelength Infrared Camera (LWIRC). LWIRC is a facility instrument for the Keck Observatory that operates over the wavelength region 7-13 microns using a 128x128 Si:As focal plane array. Features of the camera include: chopping and nodding, good stray light rejection, a high dynamic range preamplifier/ADC system, a full silicate and CVF filter set, multiple plate scales, a coronagraph, an electronic neutral density filter, and a 10 micron polarizer. LWIRC is a joint project of the Space Sciences Laboratory of UC Berkeley and LLNL.

5. LABORATORY ASTROPHYSICS

5.1 Planetary Interiors and Atmospheres

W. J. Nellis (LLNL) and collaborators continued their laboratory experiments in which they simulate the physical conditions in planetary interiors. With the recent discoveries of 60 extrasolar giant planets (EGP) and Brown Dwarfs (BD) and the imaging of EGP HD209458b, it is now known that the central temperatures of HD209458b and Saturn are about twice and half that of Jupiter (20,000 K), respectively. Central pressures of these planets are 2 TPa (1 TPa=10 Mbar). Thus, the universe appears to have a substantial amount of mass in the form of ‘‘hot’’ and ‘‘cold’’ Jupiters. Jupiter, GPs, and BDs are composed almost entirely of hydrogen. The most important conditions to study are pressures of 50 GPa to 1 TPa, densities up to 15 times initial liquid density, and temperatures of 1,000 to 40,000 K. This is the region in which highly-degenerate fluid hydrogen undergoes a complex continuous phase transition from a molecular insulator to a monatomic metal. Nellis and collaborators have recently accessed these extreme conditions in the laboratory with a reverberating shock wave. Fluid hydrogen becomes metallic at 140 GPa, ninefold compressed liquid density, and 3000 K. Because the convective motion of electrically conducting fluid hydrogen causes the magnetic fields of Jovian-type planets, a scaling relationship was derived from the data and used to calculate hydrogen electrical conductivity vs pressure (depth) in Jupiter. The results allow them to address some interesting questions about Jupiter. For example, why is its magnetic field and its asymmetry so large compared to those of the Earth, and why is there a relatively sharp core-mantle boundary in Jupiter between a molecular mantle and atomic core? Since at high shock pressures no first order phase transition has been observed in fluid hydrogen, it is unlikely that the dissociative phase transition in Jupiter is first order and, thus, unlikely that there is a core-mantle boundary. The pressure dependence of electrical conductivity suggests that maximum conductivity is reached at 0.9 RJ, rather than at 0.75 RJ, as thought previously. Magnetic fields are typically represented as multipole expansions which are proportional to r^{-n}, where r is distance from the center and n=3 for the dipolar terms. Thus, the Jovian magnetic field produced near the surface has little distance in which it’s magnitude is attenuated, nor in which its asymmetry, produced by various multipole components, is attenuated. In Saturn metallic conductivities are reached at 0.5 RS, where RS is the radius of Saturn. As a result radial attenuation is an order of magnitude greater in Saturn than in Jupiter and the Saturnian magnetic field is substantially smaller and more symmetric than that of Jupiter, even though these planets have essentially the same composition and very similar masses. Similar conclusions can be reached about EGPs and BDs, provided they can be imaged; it is the density which provides the information necessary to infer internal thermodynamic conditions.

E. Wishnow (LLNL), H. Gush, M. Halpern, I. Ozier (Univ. of British Columbia), are conducting studies of the collision-induced submillimeter spectra of low temperature gase mixtures; these studies are funded by the NASA planetary atmospheres program. The initial studies of nitrogenargon gas mixtures are pertinent to the interpretation of the anticipated Cassini far-infrared spectrum of Titan. Also under investigation is the spectrum of methane-hydrogen as it is expected to appear in the spectrum of Saturn. The measurements are being conducted using a unique differential Michelson interferometer and dual-pipe cryogenic absorption cell. The studies cover the temperature range 78 to 89 K and the spectral range 3-25 wavenumbers (3000-400 microns).

5.2 Far−UV and X−ray Spectroscopy

The laboratory astrophysics effort centered around the electron beam ion trap facility has produced wide ranging data in support of the Chandra and XMM X-ray satellite missions. These data span line formation processes in collisional plasmas, resolving puzzles in astrophysical spectra, establishing complete line lists, and investigations of cometary X-ray emission. Overviews of the effort were reported by P. Beiersdorfer and H. Chen (LLNL) in collaboration with K. Boyce, G. Brown, K. Gendreau, J. Gygax, R. Kelley, C. Stahle, and A. Szymkowiak (Goddard Space Flight Center) as well as E. Behar and S. Kahn (Columbia Univ.).

A major success was achieved when the long-standing puzzle of the anomalously small line ratio of the two dominant 3d-2p transitions in Fe XVII observed in astrophysical sources could be reproduced in the laboratory and explained in a rigorous way. First, G. V. Brown, P. Beiersdorfer, and K. Widmann (LLNL) showed that theory systematically overpredicts the line ratio not only for Fe XVII, but for all neighboring ions in the isoelectronic sequence. The ratios observed in the Sun and stellar atmospheres, nevertheless, were still smaller than those observed in the laboratory. This intimated the idea that the ratio is affected by opacity effects, albeit less than originally believed based on the theoretical line ratio. Then, P. Beiersdorfer and D. Thorn (LLNL) with their colleagues S. von Goeler and M. Bitter (Princeton University) showed that the small ratios observed in stellar atmospheres could also be observed in the laboratory without invoking opacity effects. A vigorous search for an explanation other than opacity employing the electron beam ion trap finally revealed that the Fe XVII lines were blended with lines from Fe XVI. G. V. Brown, P. Beiersdorfer, H. Chen, M. H. Chen, and K. J. Reed (LLNL) showed that the small line ratio occurs in colder plasmas with a larger abundance of Fe XVI. The ratio is, therefore, useful as a temperature diagnostic in the range 1.5 to 7 Million degrees.

In a major enhancement of the laboratory astrophysics capabilities, the electron beam ion trap had been paired with the spare engineering version of the XRS calorimeter developed at the Goddard Space Flight Center for the ASTRO-E mission. The calorimeter complements crystal and grating spectrometers by providing broadband analysis of the X-ray emission. By normalizing high-resolution crystal spectrometer data to radiative electron capture features observed with the XRS, the new capability was used by H. Chen, P. Beiersdorfer, and J. H. Scofield (LLNL) in collaboration with K. C. Gendreau, K. R. Boyce, G. V. Brown, R. L. Kelley, F. S. Porter, C. K. Stahle, A. E. Szymkowiak (GSFC) and S. M. Kahn (Columbia Univ.) to make the first absolute determination of the electron-impact excitation cross sections of the L-shell X-ray emission lines of Fe XXIV. Their measurement validated several theoretical approaches for calculating the iron L-shell emission line intensities. In parallel, detailed excitation cross sections of the strongest L-shell lines in Fe XXI, Fe XXII, Fe XXIII, and Fe XXIV were reported by P. Beiersdorfer, G. V. Brown, D. A. Liedahl, and K. J. Reed (LLNL) in collaboration with M. F. Gu, S. M. Kahn, D. W. Savin, and E. Behar (Columbia Univ.). These measurements determined the contributions from radiative cascades and resonance excitation to the line formation processes. They also quantified the contributions from unresolved dielectronic satellites, which may enhance the lines by up to 20 Again utilizing the electron beam in trap, a complete analysis of the K-shell dielectronic satellite spectrum of Ne IX was reported by B. J. Wargelin (Harvard-Smithsonian Center for Astrophysics), S. M. Kahn (Columbia Univ.), and P. Beiersdorfer (LLNL).

P. Beiersdorfer, G. V. Brown, H. Chen (LLNL), and collaborators C. M. Lisse (Space Telescope Science Institute) and R. E. Olson (University of Missouri) reported a new X-ray diagnostic for measuring the velocity of solar wind ions. Their findings came about as part of a concerted effort to simulate X-ray line formation by charge exchange between heavy highly charged ions from solar or stellar winds and neutral gases from such sources as comets or the interstellar medium. This effort was expanded last year to include C. Weatherford and B. Saha (Florida A & M University) and B. Wargelin (CfA). The project benefited greatly from the enhanced laboratory astrophysics capabilities generated by the pairing of the electron beam ion trap and the XRS microcalorimeter. This for the first time allowed fully resolved measurements of the carbon, oxygen, and neon K-shell X-ray lines produced by charge exchange.

K. B. Fournier (LLNL) and collaborators from the Johns Hopkins University carried out a series of measurements of diagnostic line emission from highly charged iron ions. In a series of experiments at the Frascati Tokamak Upgrade in Frascati, Italy, they measured the equilibrium distribution of M-shell iron charge states in a nearly single temperature plasma. Collisional-radiative models have demonstrated great sensitivity to changes in temperature in the observed spectra. These observations test ionization balance models used to unfold information from observations of emission measure distributions. They also measured electron-density sensitive ratios of L-shell iron ions at densities that are factors of a few more than what has been previously available. This work provides a laboratory benchmark for iron emission line ratios that have been used to identify high density plasma conditions in cataclysmic- variable star systems such as EX Hydrae.

R. Heeter, M. Foord, J. Emig, D. Liedahl and P. Springer (LLNL), together with J. Bailey and M. Cuneo (Sandia Nat'l Lab - Albuquerque) continued experimental measurements on the photoionization equilibrium of iron at the Sandia Z Facility. These integrated experiments provide benchmarks for models of photoionized regions such as accretion disks in X-ray binaries and AGNs. Samples are driven into photoionization equilibrium by intense X-ray pulses from the Z pinch. The equilibria are characterized by time-resolved measurements of the power, temperature and spectrum of the pinch source, and by time-resolved measurements of the density, emission and absorption spectra of the iron samples. Analysis of earlier data continues, and new experimental data for iron-magnesium-oxygen plasmas have been obtained and are now being evaluated.

5.3 Laser Astrophysics Experiments

R. I. Klein (UC Berkeley and LLNL), H. Robey (LLNL) and T. Perry (LLNL) conducted a series of new OMEGA laser experiments investigating the evolution of a high density sphere embedded in a low density medium after the interaction of a strong shock wave, thereby emulating the supernova shock-cloud interaction. The interaction of strong shock waves, such as those generated by the explosion of supernovae with interstellar clouds, is a problem of fundamental importance in understanding the evolution and the dynamics of the interstellar medium (ISM) as it is disrupted by shock waves. The physics of this essential interaction is critical to understanding the evolution of the ISM, the mixing of interstellar clouds with the ISM and the viability of this mechanism for triggered star formation. In the experiments the interaction is viewed from two orthogonal directions enabling visualization of the both the initial distortion of the sphere into a vortex ring as well as the onset of an azimuthal instability that ultimately results in the three-dimensional breakup of the ring. These studies augment the previous work on the NOVA laser by enabling the full three-dimensional topology of the interaction to be understood. They showed that the experimental results for the vortex ring are in remarkable agreement with theory and by comparing with high resolution 3D AMR numerical simulations they recovered all the essential features of the interaction. These new experimental results may shed light on implications for mixing in the ISM.

D. Ryutov (LLNL) continued to refine the theoretical criteria behind scaling astrophysics into the laboratory. His initial assessment looked at issues of ‘‘pure’’ hydrodynamics relevant to core-collapse supernovae explosions. His more recent work addresses the dynamics of radiatively driven (via a photoionization or ablation front) molecular clouds illuminated by nearby bright stars, in particular the Eagle Nebula. The central question addressed by Ryutov was the extent to which laser experiments, which deal with targets on a spatial scale of 0.01 cm and occur on a time scale of a few nanoseconds, can reproduce phenomena occurring at spatial scales of a million or more kilometers and time scales from hours to 100,000’s of years. In relation to the Eagle Nebula, Ryutov theoretically discovered two new instabilities, one triggered by thermal conductivity effects, and the other by a source of directional radiation. His current work centers around whether shock-induced turbulence in a molecular could can lead to enhanced pressure stiffness in the cloud.

P. Drake (Univ. of Michigan), in collaboration with H. Robey, J. Kane, and B. Remington (LLNL), has been developing experiments on the Omega laser at the Univ. of Rochester, aimed at issues of core-collapse supernova (SN) explosion hydrodynamics. In these experiments a high intensity laser pulse is used to drive a strong shock ($M>>1$) into the target materials. The primary issues under investigation are, in a planar 2-layer or 3-layer configuration, the difference 2D vs 3D instability evolution, and the potential transition to turbulence. Numerical simulations generally were found to provide reasonable agreement with the experiments in the moderately nonlinear regime, with experiments predicted to enter the fully turbulent regime under development.

P. Drake (Univ. of Michigan), in collaboration with T. Perry and B. Remington (LLNL), has been developing experiments on the Omega laser at the Univ. of Rochester aimed at studying radiative hydrodynamics issues relevant to supernova remnants (SNR’s). Strong shocks in low density media can lead to a radiative precursor outrunning the shock, and in extreme cases to radiative cooling. Drake and colleagues have developed a point projection absorption spectroscopy diagnostic, to measure the extent of the radiative precursor launched by the strong shock in a scaled SNR geometry. The future work will examine the effects of scaling the shock strength and ambient medium density of the radiative precursor.

K. Shigemori (Osaka University), T. Ditmire (Univ. Texas, Austin), E. Liang (Rice Univ.), in collaboration with M.J. Edwards and B. Remington (LLNL), has analyzed experiments done on the Falcon laser at LLNL to create a radiative blast wave. This work is potentially relevant to supernova-remnant and interstellar medium dynamics. A strong shock was launched into Xe gas, and a radiative precursor was diagnosed by optical interferometry. This radiative precursor was more significant for higher atomic-number gas. A complication of the laser experiment is the role played by electron thermal heat conduction, which is thought to be insignificant in SNR shocks. A final analysis, with 1D radiation-hydrodynamics modeling, showed that the precursor region near to the shock front was caused by electron heat conduction, while the long-range component of the precursor was due to radiation. Future experiments are being considered, using a magnetic field to reduce the effect of the electron heat conduction.

M. Pound (Univ. of Maryland), in collaboration with D. Ryutov, J. Kane, and B. Remington (LLNL), have developed a model of the hydrodynamics of photoevaporation fronts, such as the Eagle Nebula. The towering ’Pillars of Creation’ of the Eagle Nebula are a long-standing astrophysical mystery. In the Rayleigh-Taylor instability model, radiation from nearby stars photoevaporate and accelerate the cloud surface, and the Pillars are falling ’spikes’ of dense gas. The model reproduces recently measured fluid velocities in the Pillars, assuming the radiation drive and resulting acceleration decrease with time, and the density profile along the pillars. Theoretical and numerical evaluations of this model are ongoing, and the possibility of scaled verification experiments using intense lasers is being considered. This work was successfully proposed as an ATP proposal to NASA, and 3 years of funding were secured.

PUBLICATIONS

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