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## 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 C. Alcock, K. Cook, and W. van Breugel. In addition, B. Macintosh and S. Marshall are staff members and there are several full-time postdoctoral fellows and researchers: S. Blais-Ouellette, A. Drake, W. de Vries, M. Hammergren, M. Lacy, S. Laurent-Muehleisen, J. Patience, and P. Popowski. C. Max (director of the University Relations Program) and S. Gibbard are LLNL staff closely associated with IGPP. 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. Ziocck 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 C. Alcock, K. Cook, A. Drake, S. Marshall, C. Nelson, and P. Popowski (LLNL); R. Allsman, T. Axelrod, K. Freeman, and B. Peterson (Mt. Stromlo Obs., Australia); A. Becker, C. Stubbs, and A. Tomaney (CfPA at U/Washington); K. Griest and T. Vandehei (CfPA at UC San Diego); D. Alves (STScI); D. Bennett (Notre Dame); M. Geha (UC Santa Cruz); M. Lehner (U/Sheffield); D. Minniti (P. Universidad Católica, Chile); P. Quinn (European Southern Obs., Germany); W. Sutherland (Oxford University); and D. Welch (McMaster University).

The Milky Way's dark matter is thought to be distributed in a large, spherical halo. Its constitution is unknown, because it emits no detectable radiation. Most hypotheses for its constitution before the Project involved speculations from particle physics. This experiment searches for planets, brown dwarfs, and black holes or any other massive objects (MACHOs) having a mass range of  $10^{-7}M_{\text{Sun}} < M < 30M_{\text{Sun}}$ .

If the dark matter consists of MACHOs, it will occasionally magnify light from extragalactic stars by the gravitational lensing effect. An event can be recognized by fitting a theoretical light curve to the observations (four-parameter fit) and by its lack of color variation (achromaticity). Unambiguous recognition of microlensing requires an adequate number of data points on the light curve and measurements in at least two filter bands. To detect events, one must monitor millions of stars for several years because the probability of a micro-

lensing event is very low. The experiment operated for eight years and collected last data in December 1999.

The MACHO Project used the 130-cm reflecting telescope of the Mt. Stromlo Observatory, near Canberra, Australia. Operating at prime focus with an innovative optical system gave a field of view 1 deg in diameter. MACHO used a dichroic filter for simultaneous imaging in a blue and a red spectral band, doubling the effective exposure rate.

The MACHO Project has been monitoring fields in two satellite galaxies of the Milky Way, the Large and Small Magellanic Clouds (LMC; SMC), as well as fields toward the center of the Milky Way. The Project has accumulated almost 8 TBytes of image data and about 600 Gbytes of photometry on about 70 million stars. Data were reduced in near real time, and microlensing events were often identified well before their peak.

The Project sent out alert announcements to the world, which were also posted on its web site (<http://darkstar.astro.washington.edu/>). These alert announcements were used by different groups throughout the world to search for planets and to study ongoing microlensing events in detail.

Ongoing microlensing has also been used to study the source star in greater detail than possible without the magnification. Members of the Project have obtained high S/N Keck echelle spectra of main sequence stars in the bulge of the Milky Way for detailed abundance calculations, getting scheduled time during the bulge season knowing that there would be ongoing microlensing events with main sequence source stars (Minniti *et al.* 1998, ApJ, 499, L175).

The MACHO project released a few milestone analyses last year. They reported on the search for microlensing towards the LMC (Alcock *et al.* 2000, ApJ, 542, 281). Analysis of 5.7 years of photometry on 11.9 million stars in the LMC reveals 13 – 17 microlensing events depending upon the selection criteria. A detailed treatment of the detection efficiency shows that this is significantly more than the  $\sim 2$  to 4 events expected from lensing by known stellar populations. They estimate the microlensing optical depth towards the LMC to be  $\tau_{\text{LMC}} = 1.2^{+0.4}_{-0.3} \times 10^{-7}$ , with an additional 20% to 30% of systematic error. The spatial distribution of events is mildly inconsistent with LMC/LMC disk self-lensing, but is consistent with an extended lens distribution such as a Milky Way or LMC halo. Interpreted in the context of a Galactic dark matter halo, consisting partially of compact objects, a maximum likelihood analysis gives a MACHO halo fraction of 20% for a typical halo model with a 95% confidence interval of 8% to 50%. A 100% MACHO halo is ruled out at the 95% C.L. for all except the most extreme halo model. Interpreted as a Galactic halo population, the most likely MACHO mass is between  $0.15M_{\text{Sun}}$  and  $0.9M_{\text{Sun}}$ , depending on the halo model, and the total mass in MACHOs out to 50 kpc is found to be  $9^{+4}_{-3} \times 10^{10}M_{\text{Sun}}$ , independent of the halo model. These results are marginally consistent with the previous MACHO results (Alcock *et al.* 1997, ApJ, 486, 697), but are lower by about a factor of two. This is mostly due to Poisson noise because with 3.4 times more exposure and increased sensitivity to long timescale events, the Project did not find the expected factor of  $\sim 4$

more events. Besides a larger data set, this work also includes an improved efficiency determination, improved likelihood analysis, and more thorough testing of systematic errors, especially with respect to the treatment of potential backgrounds to microlensing. They stress that an important source of background are supernovae (SNe) in galaxies behind the LMC.

On another front, the MACHO Collaboration made substantial progress toward analyzing a few hundred events toward the Galactic bulge. Previous analyses by three, different teams indicated a very high microlensing optical depth, which was inconsistent with other measurements and Galactic models.

MACHO presented the microlensing optical depth towards the Galactic bulge based on the detection of 99 events found in their Difference Image Analysis (DIA) survey (Alcock *et al.* 2000, ApJ, 541, 734). This analysis encompasses three years of data, covering  $\sim 17$  million stars in  $\sim 4 \text{ deg}^2$ . The DIA technique improves the quality of photometry in crowded fields, and allows the MACHO Collaboration to detect more microlensing events with faint source stars. They find this method increases the number of detected events by 85% compared with the standard analysis technique. The total microlensing optical depth is estimated to be  $\tau_{\text{total}} = 2.43^{+0.39}_{-0.38} \times 10^{-6}$  averaged over 8 fields centered at  $(l, b) = (2.^{\circ}68, -3.^{\circ}35)$ . For the bulge component they find  $\tau_{\text{bulge}} = 3.23^{+0.52}_{-0.50} \times 10^{-6}$  assuming a 25% stellar contribution from disk sources. These optical depths are in good agreement with the past determinations of the MACHO (Alcock *et al.* 1997) and OGLE (Udalski *et al.* 1994) groups, and are higher than predicted by contemporary Galactic models. The Project shows that the observed event timescale distribution is consistent with the distribution expected from normal mass stars, if one adopts the stellar mass function of Scalo (1986) as the lens mass function. However, they note that other mass functions are not excluded by this analysis.

The first results from a new, expanded analysis of the MACHO bulge microlensing events with clump giants as sources were reported by Popowski *et al.* (2000; astro-ph/0005466). This class of events allows one to obtain robust conclusions because relatively bright clump stars are not strongly affected by blending effects. MACHO gives the preliminary average optical depth of  $\tau_{\text{bulge}} = (2.0 \pm 0.4) \times 10^{-6}$  at  $(l, b) = (3.^{\circ}9, -3.^{\circ}8)$ , which is somewhat lower than the previously derived values, and so in lesser conflict with other observational and theoretical constraints. The analyses of the spatial distribution of the bulge optical depth and the mass function of the lenses are underway.

Using a standard frequency detection algorithm MACHO analyzed over 1300 variables classified provisionally as first-overtone RR Lyrae pulsators in the MACHO variable-star database of the LMC (Alcock *et al.* 2000, ApJ, 542, 257). They find that 70% of the total population is monoperiodic. Several types of RR Lyrae pulsational behavior are clearly identified for the first time from this sample. This study increased the number of known double-mode stars in the LMC to 181. The Project also discovered two additional types of multifrequency pulsators with low occurrence rates of 2% for each. In one of these types, the frequency components are

closely spaced and symmetric relative to the central component. None of the current theoretical models are able to explain the observed close frequency components without invoking non-radial pulsation components in these stars.

In a related work, MACHO has detected 90 objects with periods and light-curve structures similar to those of field  $\delta$ -Scuti stars (Alcock *et al.* 2000, ApJ, 536, 798). The majority of these objects lie in or near the Galactic bulge. One of these objects may be an evolved non-radial pulsator. The amplitude distribution of these sources lies between those of low- and high-amplitude  $\delta$ -Scuti stars, which suggests that they may be an intermediate population. The majority of these objects are evolved stars pulsating in fundamental or first overtone radial modes.

P. Popowski & C. Alcock (LLNL) investigated a problem of correcting parameters of events based on the ‘‘entropy’’ of a microlensing ensemble. They show how the fact that a group is more than just a collection of individuals reveals itself in the case of microlensing. They derive formulae for correcting the distribution of the dimensionless impact parameters of events,  $u_{\min}$ . They refer to the case when undetected biases in the  $u_{\min}$ -distribution can be alleviated by multiplication by a common constant factor. They show that in this case the general maximum likelihood problem of solving an infinite number of equations reduces to two constraints, and they find an analytic solution. Under the above assumptions, this solution represents a state in which the ‘‘entropy’’ of a microlensing ensemble is at its maximum, that is, the distribution of  $u_{\min}$  resembles a specific box-like distribution to the highest possible extent. They also show that this technique does not allow one to correct the parameters of individual events on the event by event basis independently from each other.

Continuing his work on the distance scale, P. Popowski (LLNL) explored the consequences of making the RR Lyrae and clump giant distance scales consistent in the solar neighborhood, Galactic bulge and Large Magellanic Cloud (LMC). He employs two major assumptions: 1) that the absolute magnitude - metallicity,  $M_V(RR) - [Fe/H]$ , relation for RR Lyrae stars is universal, and 2) that absolute  $I$ -magnitudes of clump giants,  $M_I(RC)$ , in Baade’s Window are known (e.g., can be inferred from the local Hipparcos-based calibration or theoretical modeling). A comparison between the solar neighborhood and Baade’s Window sets  $M_V(RR)$  at  $[Fe/H] = -1.6$  in the range  $(0.59 \pm 0.05, 0.70 \pm 0.05)$ , somewhat brighter than the statistical parallax solution. More luminous RR Lyrae stars imply younger ages of globular cluster, which would be in better agreement with the conclusions from the currently favored stellar evolution and cosmological models. A comparison between Baade’s Window and the LMC sets the  $M_I^{LMC}(RC)$  in the range  $(-0.33 \pm 0.09, -0.53 \pm 0.09)$ . The distance modulus to the LMC is  $\mu^{LMC} \in (18.24 \pm 0.08, 18.44 \pm 0.07)$ . Unlike  $M_I^{LMC}(RC)$ , this range in  $\mu^{LMC}$  does *not* depend on the adopted value of the dereddened LMC clump magnitude,  $I_0^{LMC}(RC)$ . Popowski argues that the currently available information is insufficient to select the correct distance scale with high confidence.

C. Nelson, K. Cook, P. Popowski (LLNL), and D. Alves

(STScI) presented UBV photometry of the eclipsing binary Harvard Variable 2274 in the LMC (Nelson *et al.* 2000). The stellar parameters of this binary system were recently calculated by Guinan *et al.* (1989), who gave both a reddening toward HV 2274 of  $E(B - V) = 0.083 \pm 0.006$  and a distance modulus to the LMC of  $\mu_{LMC} = 18.42 \pm 0.07$ . The reddening of this system was also determined by Udalski *et al.* (1998), who found  $E(B - V) = 0.149 \pm 0.015$ . With Udalski *et al.* (1998) B and V photometry, Guinan *et al.* (1998) obtained  $E(B - V) = 0.12 \pm 0.009$  and  $\mu_{LMC} = 18.30 \pm 0.07$ . Using their UBV photometry, Nelson and collaborators derive a reddening of  $E(B - V) = 0.088 \pm 0.023$ , consistent with the original value of Guinan *et al.* and supporting a slightly longer distance modulus to the LMC of about  $\mu_{LMC} = 18.40 \pm 0.07$ . Nelson *et al.* stress the uncertainties inherent in ground-based UBV photometry and the concomitant uncertainties in determining distances based upon such photometry.

## 2.2 Kuiper Belt Objects

C. Alcock, K. Cook, S. Marshall, and R. Poratta (LLNL) in collaboration with I. de Pater, C. Liang, and J. Rice (UC Berkeley), J. Lissauer (NASA/Ames), T. Axelrod (MSSSO, Australia), S. King, T. Lee, A. 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) are working on the Taiwan-American Occultation Survey (TAOS). TAOS will perform a census of small objects ( $>2$  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 the first half of 2001.

## 2.3 Gamma Ray Bursts

S. Marshall (LLNL) in collaboration with C. Akerlof, R. Kehoe, B. Lee, and T. McKay (U/Michigan), R. Balsano, J. Bloch, D. Caspersen, S. Fletcher, G. Gisler, J. Hills, W. Priedhorsky, J. Szymanski, T. Vestrand and J. Wren (LANL) continued his work on the ROTSE (Robotic Optical Transient Search Experiment) collaboration. ROTSE is an experimental program to search for astrophysical optical transients on time scales of a fraction of a second to a few hours. This is an area of astronomical science that has been relatively unexplored until now. The primary incentive for this research is to find the optical counterparts of gamma-ray bursts (GRBs). These mysterious events are manifested by brief ( $\sim 10$  seconds) intense flashes of gamma-rays with typical photon energies of the order of 1 MeV.

The first phase of this project, ROTSE-I, comprises a  $2 \times 2$  array of wide field cameras with 200 mm,  $f/1.8$ , telephoto lenses on a fast slewing mount. The 16 degree field of view has a limiting visual magnitude of approximately 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 began in early 1998. The system operates in an all sky survey mode while it waits for the occasional gamma-ray burst trigger signal. On January 23, 1999 the system detected the first known prompt optical counterpart to a GRB. This burst counterpart, reached 9th magnitude at its observed peak and was detected a 7 times over  $\sim 10$  minutes down to a magnitude of 14.5 (Akerlof *et al.* 1999). More recently a search for gamma ray burst optical counterparts in six of ROTSE-I triggered bursts was published by Akerlof *et al.* (2000). No optical counterparts were observed, implying that optical and gamma ray emission are not strongly correlated.

G. Mathews (Notre Dame U.), J. Wilson and J. Salmonson (LLNL) have continued their work on neutron star binaries and their relation to gamma ray bursts. The results provide a satisfactory model for many gamma ray bursts and have been published by Mathews (2000) and Salomonson *et al.* (2000). H. Dalhed and J. Wilson developed a tabular equation of state which is being used in the Mayle-Wilson supernova computer model.

H. Park (LLNL) and G. Williams (U Arizona) are working on the LOTIS/Super-LOTIS telescopes that attempt to promptly respond to gamma-ray burst triggers and measure early time optical light curves associated with them. The sensitivity of these systems are 14 – 19 magnitude and the response time is 5 – 30 seconds. In response to the HETE-II launch, LOTIS will now have 4 cameras viewing the same field-of-view with R,V,B and clear filters simultaneously. The Super-LOTIS system has been moved to Kitt Peak in Arizona in April 2000 and is ready for the HETE-II triggers.

#### 2.4 Hydrodynamics Simulations of Star Formation Processes

R.I. Klein (LLNL, and UC Berkeley) with his graduate student R. Fisher (UC Berkeley) and C. McKee (UC Berkeley) studied 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 (AMR). Previous work introducing random noise perturbations injects power on a small numerical scale which is much less than the Jeans length for a stable core. The outcome of such calculations depends sensitively on the amplitude of the initial perturbations which is arbitrarily chosen. Because the spectrum and the amplitude is entirely ad-hoc, it is difficult to relate the problem to a real physical system and so any conclusions toward a  $\alpha - \beta$  criterion is not meaningful from an astrophysical perspective. Previous models of collapsing cloud cores typically start with clouds that are very far from equilibrium leading to highly supersonic collapse. This conflicts with observations of the statistics of pre-stellar vs. embedded stellar molecular cloud cores which show that the core is in an approximate state of equilibrium with near sonic collapse.

To examine more realistic models of protostellar formation, Klein and collaborators investigated self-consistent hydrodynamic equilibria of rotating, marginally stable, initially isothermal cloud cores. These models have radii, masses,

density contrasts, turbulent line-widths and projected velocity gradients consistent with observations of low mass molecular cloud cores. The initial cloud is assigned a turbulent velocity perturbation consistent with Larson's linewidth size relation. The 3-D models are evolved in time under fully coupled self-gravitational hydrodynamics with adaptive mesh refinement using a non-isothermal equation of state that is a barotropic transition from isothermal to adiabatic collapse. They examined several properties of the resulting protostellar cores and are studying the qualitative nature of the fragmentation process in realistic cloud cores; the transition from single to binary and multiple stars; the formation of misaligned binary systems and the role played by filament formation in the formation of stars. Klein has recently been awarded a large block of computer time on the parallel supercomputers at San Diego (NPACI) for this research with Fisher and McKee.

R.I. Klein (LLNL, and UC Berkeley) in collaboration with J. Walters and C. McKee (UC Berkeley) is performing 2-D and 3-D hydrodynamic simulations of the formation of the Western Cloud edge in the Cygnus Loop supernova remnant. Using their 3-D AMR hydrodynamics code, they are performing detailed simulations to obtain the structure of the cloud-shock interaction of the Western edge. These simulations are coupled with a spectroscopic code to obtain the detailed ionization history of the interaction and produce a detailed spectrum. The spectrum will be compared with recent CHANDRA and ROSAT observations of the Cygnus Loop. These calculations will be used to elucidate the initial conditions in the Cygnus Loop SNR.

R.I. Klein (LLNL, and UC Berkeley), R. Crockett (UC Berkeley graduate student), C. McKee (UC Berkeley) and Phil Collela (LBNL) are developing a new 3-D high order accurate MHD code with adaptive mesh refinement. They are employing Godunov hydrodynamic techniques to follow multi-dimensional shocks with great accuracy. This year has been spent in extensive testing of the code. They are beginning to investigate a series of MHD instabilities in the interstellar medium.

#### 2.5 3-D Simulations of Stellar Structure and Evolution

D. Dearborn, with G. Bazan, K. Cook, D. Dossa, P. Eggleton, P. Eltgroth, R. Eastman, S. Murray, C. Nelson, I. Otero, B.S. Pudliner and A. Taylor (LLNL) have begun a significant program ("Djehuty") to develop a 3-D stellar evolution code running on massively parallel computing systems. Stars provide the fundamental metric for studying the universe: its size, age and composition. Three dimensional (3-D) phenomena are important in all stars, but to date these effects have been modeled through coarse approximation. LLNL's massively parallel computer systems coupled with the intense ASCII coding efforts has uniquely situated the Lab to improve our physical understanding of stellar properties by providing a quantitative capability to study three dimensional phenomena. Under an Laboratory Directed Research and Development (LDRD) sponsored Strategic Initiative they have commenced a cooperative effort between Defence and Nuclear Technologies (DNT), Physics and Advanced Technologies, and the Center for Applied Scientific

Computing (CASC) to begin development of Djehuty as unique tool to study global 3-D processes in stellar structure and evolution. It will operate on massively parallel machines with the best available physical data (opacities, equations of state, etc.) as well as new algorithms tailored specifically for the MPP environment.

In the first year of operation, the recruitment of the core team has been completed, and it has taken the first steps in developing Djehuty. An analytic equation of state, consistent with the best LLNL tabulations, and an elementary gravity routine has been combined with other components to form the basic framework. A small 3-D stellar model (1.6 million zones) was generated and successfully executed a hydrodynamic simulation of this model on the TC2K computer system at LLNL. Additional tests are being made to ensure the accuracy of the simulations, and to develop methodologies for efficiently performing and analyzing 3-D stellar structure calculations. The experience gathered implementing an astrophysical equation of state facilitates the addition of other physics, including astrophysical opacities and nuclear energy generation. Work has also begun to include diffusive energy transport. When this is complete, the first calculations will be made aimed at studying the long standing problem of convective core overshoot.

In a related effort C. Nelson, P. Eggleton and D. Dossa (LLNL) are investigating the link between the initial and final configurations of binary stars. Using the power of the LC TeraCluster with standard 1-D approximations they have completed a survey that exceeds all the computation ever done on this subject. Analysis of these results will provide insight into the most interesting binary problems for Djehuty. The ability to distort the structure for modeling non-spherical (binary) objects should be included over the next year.

## 2.6 Stellar High Energy Astrophysics

R.I. Klein (LLNL, and UC Berkeley) and G. Jernigan (UC Berkeley, SSL) made the first time-dependent, multi-dimensional, radiation hydrodynamical calculations of the plasma flow of super-Eddington accreting neutron stars through hollow cone accretion columns. Filled accretion columns are expected when accretion occurs from a wind or from a thick disk, since most of the field lines from a pole become loaded with accreting matter. In thin disk accretion, however, one encounters hollow cones, an extreme form of transverse structure in the polar accretion flow. In this instance, the field lines connected to the center of the pole are likely to be open, with the matter crossing the inner boundary layer of the disk onto the field lines whose stellar foot print forms a partial or complete ring around the magnetic axis. Such a configuration is extremely interesting, since the optically thick walls of the accretion "funnel" can force the radiation emitted into the hollow interior of the column to emerge as a radiation pencil beam or jet. These initial studies allow the investigation for a range of values of accretion luminosity; surface magnetic field and polar cap extent. For example, Klein and collaborators are investigating the properties of hollow cone accretion models for Photon Bubble Oscillations (PBO) and photon bubble turbulence, which they discovered this past year in the X-ray pulsar Cen X-3.

The formation of PBO in hollow cone accreting X-ray pulsars is contrasted with PBO formation in uniformly filled accretion columns. Preliminary calculations indicate that photon bubble formation in the hollow cone accretion columns may be used as probes of the structure of the accretion columns for an X-ray pulsar.

D. Liedahl (LLNL) has led a project to develop an X-ray spectral code known as the Livermore X-Ray Spectral Synthesizer (LXSS), which is nearing completion, and which will be released to the public shortly thereafter. Co-designed by C. Mauche and K. Fournier (LLNL), LXSS provides access to and manipulation of a large database of atomic data, and is intended to facilitate analyses of high-resolution spectroscopic data, such as is being returned by Chandra and XMM-Newton.

C. Mauche (LLNL) and J. Raymond (CfA) analyzed photometric and spectroscopic observations with the Extreme Ultraviolet Explorer (EUVE), taken over a period of three days in March 1997, of the eclipsing SU UMa-type dwarf nova OY Carinae when it was in superoutburst. Because of the longer time on source, the larger number of eclipses observed, and the higher count rate in the detector, they were able to significantly strengthen previous reports that there is little or no eclipse by the secondary of the EUV emission region of OY Car in superoutburst. The EUVE spectrum extends from 70 to 190 Angstroms and contains broad (FWHM 1 Angstrom) emission lines of N V, O V-VI, Ne V-VII, Mg IV-VI, Fe VI-VIII, and possibly Fe XXIII. Good fits of the observed spectrum were obtained with a model (similar to that of Seyfert 2 galaxies) wherein radiation from the boundary layer and accretion disk is scattered into the line of sight by the system's photoionized accretion disk wind. Because radiation pressure alone falls an order of magnitude short of driving such a wind, it appears that magnetic forces must also play a role in driving the wind of OY Car in superoutburst.

C. Mauche (LLNL), R. Hynes (Univ. of Southampton), C. Haswell, S. Chaty (Open Univ.), C. Shrader (GSFC), and W. Cui (MIT) observed with the Extreme Ultraviolet Explorer (EUVE) the newly discovered X-ray transient XTE J1118 +480 during the rising phase of the source's 2000 April outburst. These were the first EUV photometric and spectroscopic observations of an X-ray transient, made possible by XTE J1118's unusual high Galactic latitude and very low absorption line of sight. Together with Rossi X-ray Timing Explorer (2-100 keV), Hubble Space Telescope (1150-10000 Angstrom), United Kingdom Infrared Telescope (JHKL'M'), and radio telescope data, they obtained unprecedented spectral coverage of an X-ray transient. The flat IR-UV continuum appears to be a combination of optically thick accretion disk and possibly synchrotron emission, while at higher energies a typical low hard state power law was seen. EUVE observations reveal no periodic modulation, suggesting an inclination low enough that no obscuration by the disk rim occurs. They concluded that the outburst of XTE J1118 was more akin to the minioutbursts seen in GRO J0422+32 than to a normal X-ray transient outburst.

P. Wojdowski, D. Liedahl (LLNL), and M. Sako (Columbia) used spectra obtained with ASCA to study the mass and

velocity distributions in the stellar wind in the high-mass X-ray binary system Cen X-3. It was found that the X-ray spectrum could be reproduced by a wind velocity distribution similar to that given by the Castor, Abbott, & Klein model. This is surprising, given that the intense X-ray source ionizes away all ions that provide opacity to the UV field of the companion star.

## 2.7 Galaxies and Clusters of Galaxies

S. Blais-Ouellette (LLNL), C. Carignan (U of Montreal, Canada), P. Amram (LAM, France) and S.Cote (HIA, Canada) have studied the precise kinematics of late type spiral galaxies. They found that rotation curves of the smaller galaxies are rising too slowly when compared to the prediction of cold dark matter simulations. The slope of the inner density profile,  $\gamma$ , is lower than 0.6 for galaxies with maximum rotational velocity below 100 km/s, compared to  $\gamma > 1$  for CDM simulations. They are now completing the study with a larger sample, extended to cover a wide span of morphological types.

With D.N.C. Lin (UC Santa Cruz), S. Murray is continuing an examination of the multiphase evolution of gas in young galaxies. In the gaseous envelope of protogalaxies, thermal instability leads to the formation of a population of cool fragments which are confined by the pressure of a residual hot background medium. In order to remain in a quasi-hydrostatic equilibrium, the residual gas evolves at approximately the virial temperature of the dark matter halo. Its density is determined by the requirements of thermal equilibrium. The hot gas is heated by compression and shock dissipation. The heating is balanced by direct energy loss due to bremsstrahlung emission, and by conductive losses into the cool clouds, which are efficient radiators. The cool fragments are photoionized and heated by the extragalactic UV background and nearby massive stars. Several processes are discussed which determine the size distribution of the cool fragments. One-dimensional hydrodynamic simulations have been made of the evolution of the hot and cool gas. Density distributions for the two phases and for the stars have been computed for several cases, parametrized by the circular speeds of the potentials. The projected stellar distributions are found to be similar to those in the spheroidal components of galaxies. Under some conditions, primarily low densities of the hot gas, conduction is more efficient than radiative processes at cooling the hot gas, limiting the x-ray radiation from the halo gas, providing a possible explanation for the absence of strong x-ray emission from galaxies at large redshift.

S.A. Stanford and graduate student J. Whalen (UC Davis, and LLNL) searched for high redshift galaxy clusters using bent double radio sources selected from the FIRST (Faint Images of the Radio Sky at Twenty Centimeters) survey by R. Becker and M. Gregg (UC Davis, and LLNL). Optical imaging was carried out at the Lick 3 m telescope in two runs and IR imaging at the MDM observatory on Kitt Peak in one run. Combining these data, several moderate redshift cluster candidates have been identified for spectroscopic followup.

S.A. Stanford and B. Holden (UC Davis, and LLNL) obtained deep X-ray images of three high redshift clusters using the Chandra Observatory. These data were analyzed to determine the temperature of the hot gas in two of the clusters and the morphologies of all three. The results were presented by Stanford at a galaxy clusters conference in Paris, and two papers are being prepared. S.A. Stanford and B. Holden also continued a program in collaboration with P. Rosati (ESO) and P. Eisenhardt (JPL) of identifying high redshift cluster from an X-ray survey by obtaining spectroscopy of candidates at the Keck Observatory. These observations found 5 new clusters at redshifts between 0.5 and 1. Based on this sample, a proposal was submitted and approved to obtain deep X-ray data with the Chandra Observatory.

## 2.8 Active Galaxies and Quasars

R. Becker, S. Laurent-Muehleisen, and M. Gregg (UC Davis, and LLNL) in collaboration with R. White (STScI) and D. Helfand (Columbia Univ.) continued to collect and analyze new VLA observations for the FIRST survey imaging the radio sky at 1400 MHz. During the past year approximately 300 hours of VLA time were awarded to expand the survey area to  $\sim 8000$  sq. degrees. Most of the new area was between 8 and 17 hours Right Ascension and 5 to 20 degrees Declination. This same team, in collaboration with M. Brotherton (NOAO) also completed a bright quasar survey over the initial 3000 square degrees of the FIRST survey. A paper was published presenting spectra of the  $\sim 600$  quasars found in the program by White *et al.* (2000). In a related paper, the radio properties of the 30 BAL quasars in the sample were discussed (Becker *et al.* 2000).

In 2000, R. Becker (UC Davis) in collaboration with R. White (STScI) and D. Helfand (Columbia) initiated a radio survey of the Galactic plane at 1400 MHz using the VLA. In the first year of the project, the longitude range between 19-32 degrees will be imaged using the B-, C-, and D-configurations of the VLA.

S. Blais-Ouellette (LLNL), M. Reuland (LLNL, Leiden Observatory, UC Davis) and W. van Breugel (LLNL) are investigating the possible presence of giant Ly- $\alpha$  halos around powerful radio galaxies using the Taurus Tunable Filter on the Anglo Australian Telescope (Australia). Preliminary results have shown many Ly- $\alpha$  emitters around MRC 0943-242 at a distance reaching 50 kpc. Using the great versatility of the tunable filter technology, they are now extending observations to a representative sample of powerful radio galaxies.

G. Canalizo (U Hawaii, and LLNL) and A. Stockton (U Hawaii) have estimated ages for the stellar populations of low-redshift QSO host galaxies that have infrared characteristics similar to those of ultraluminous infrared galaxies (ULIRGs). There is a clear connection between interactions, starbursts, and QSO activity in these objects, and their youth suggests that they represent a short-lived transition phase between ULIRGs and classical QSOs.

C. De Breuck (LLNL graduate student guest, and Leiden Observatory), W. van Breugel (LLNL) and Leiden Observatory colleagues H. Rottgering and G.K. Miley constructed a

large sample (669 sources) of very high redshift radio galaxy candidates. The sources were taken from the recently completed Westerbork Northern Sky Survey (WENSS), the Faint Images of the Radio Sky at Twenty cm survey (FIRST), the NRAO Very Large Array (VLA) Sky Survey (NVSS), and other surveys, using Ultra Steep Spectrum (USS) selection. The total sample contains 669 sources with a 20 cm flux density larger than 10 mJy and covers virtually the entire sky outside the Galactic plane. The sample forms the basis for an intensive campaign to obtain a large sample of high redshift ( $z > 3$ ), massive forming galaxies that is selected in a way that does not suffer from dust extinction or any other optical bias. The success of this method was illustrated by the discovery of the most distant radio galaxy known, TN J0924–2201 at  $z = 5.19$ .

C. De Breuck (LLNL graduate student guest, and Leiden Observatory), 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 several significant correlations. A 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 an un-pressurized, low density region. Other correlations provide evidence for a common energy source for the radio power and total emission line luminosity, as also found in flux density-limited samples of radio sources. Using emission-line ratios 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 ratios, which are closer to high velocity shock model predictions than to the line ratios expected for pure AGN photoionization. It was found that shock dominated ionization seems to occur mostly in the smallest radio sources.

W. de Vries (LLNL), P. Barthel (Univ. of Groningen, The Netherlands), and C. O’Dea (STScI) continued their research on galaxy hosts of compact radio sources. Utilizing the high angular resolution of HST, both in the optical (WFPC2, R band, narrow band LRF) and the near-IR (NICMOS, J and K bands), significant inroads to the nature and evolution of these radio sources have already been made. Furthermore, cycle 8 STIS observations will be used to study the kinematic and physical properties of the emission line gas interacting with the expanding radio plasma. These data, combined with existing observations, will yield robust constraints on the evolution of powerful radio sources.

M.D. Gregg, in collaboration with R. Becker (UC Davis), M. Brotherton (NOAO), S. Laurent-Muehleisen (UC Davis), M. Lacy (LLNL, and UC Davis), and R. White (STScI) discovered a remarkable quasar, FIRST J101614.3+520916 (Gregg *et al.* 2000). Its optical spectrum shows unambiguous broad absorption lines (BALs) while its double-lobed radio morphology and luminosity clearly indicate a classic Fanaroff-Riley Type II radio source, a combination once

thought never to occur. Its radio luminosity places it at the extreme of the recently established class of radio-loud broad absorption line quasars (Becker *et al.* 2000). Its hybrid nature may indicate that FIRST J101614.3+520916 is a typical FR-II quasar which has been rejuvenated as a broad absorption line (BAL) quasar. When combined with the evidence presented by Becker *et al.* (2000) for a sample of 29 BAL quasars, the implication is that, contrary to most ‘‘unification by orientation’’ schemes for understanding quasar properties, no preferred viewing orientation is necessary to observe BAL systems in a quasar’s spectrum. This, and the probable young nature of the radio source in FIRST J101614.3+520916, leads naturally to the alternate picture in which the BAL phenomenon is an early evolutionary stage in the lives of quasars.

D. Proctor (LLNL) used pattern recognition techniques to automate selection of bent-double sources from the FIRST survey database. Such sources may then be used as tracers for clusters of galaxies (Blanton, et al., 2000). The task is complicated by the low resolution (in a pattern recognition sense) of the images, chance superposition of sources, the ambiguous nature of visual classifications and considerable variation in bent morphology. Decision tree and artificial neural network methods are compared and show substantially equivalent results. Resulting classifiers provide well-defined samples for future studies.

M. Lacy (LLNL and UC Davis) has begun a program to study the clustering of radio galaxies at moderate redshifts. Radio galaxies, which are found associated almost exclusively in giant elliptical galaxies and typically in poor cluster environments, should make excellent tracers of large-scale structure at high redshift. The pilot stage of this project, involving taking spectra for  $\approx 30$  radio galaxies at Lick Observatory and the Nordic Optical Telescope has been completed. This has resulted in the first detection of radio galaxy clustering at  $z \sim 0.3$ .

M. Lacy (LLNL and UC Davis), in collaboration with A. Bunker (IoA, Cambridge, UK) and S. Ridgway (Johns Hopkins University), has completed a near-infrared study of high redshift radio galaxies from the 7C3 sample, a sample significantly fainter in radio flux than most previously-studied samples of powerful radio sources. This allows the redshift-luminosity correlation present in all single flux-limited samples to be broken. Only a weak dependence of radio luminosity on host galaxy mass is found, and hosts of radio galaxies continue to be massive elliptical galaxies out to  $z \sim 2$ . This is consistent with a supermassive, billion solar mass black hole, and a correspondingly massive host galaxy, being necessary to produce powerful radio jets. Beyond  $z \sim 2.5$  there is evidence for evolution in the population, consistent with results from studies at sub-mm wavebands, and detailed morphological studies of high redshift radio galaxies. It is suggested that the hosts of radio galaxies may form early due to the high baryon densities at the centers of the most massive dark halos in the early Universe.

M. Lacy (LLNL, and UC Davis), in collaboration with M. Wold (Stockholm), P.B. Lilje (Oslo) and S. Serjeant (Imperial College, UK) has continued a program to study the cluster environments of quasars at  $0.5 < z < 0.8$ . It is found that

the environments of radio-quiet and radio-loud quasars are indistinguishable, with both being found in environments ranging from isolated to moderately-rich clusters. The typical environment is an Abell Class 0 cluster. This is consistent with recent HST-based studies of the hosts and environments of luminous quasars at low redshifts, and suggests little evolution in quasar environments has taken place between  $z \sim 0.7$  and the present day.

M. Sako, S. Kahn, F. Paerels (Columbia), and D. Liedahl (LLNL) used spectra obtained with the Chandra High Energy Transmission Grating to study X-ray line emission in the ionization cone of the Seyfert 2 galaxy Mrk 3. It was shown that the soft X-ray emission is spatially extended along the O III ionization cone, and is a hybrid of recombination emission in X-ray photoionized gas and resonantly scattered emission. The X-ray spectral properties are qualitatively consistent with those of a typical Seyfert 1 galaxy viewed at a different orientation, providing further evidence for the existence of an obscured Seyfert 1 nucleus in Mrk 3.

S.A. Stanford (UC Davis, and LLNL) continued a program with van Breugel (LLNL) of studying ultraluminous IR galaxies at high redshifts. The first phase survey results are in press (Stanford *et al.* 2000). The second phase has begun, in collaboration with UC Berkeley graduate student E. Halderson and postdoctoral fellow G. Canalizo (LLNL), in which the expanded sample of FIRST radio sources was matched with the IRAS faint source catalog and then cross correlated with bright star catalogs to identify targets for adaptive optics imaging at Lick and Keck Observatories.

W. van Breugel (LLNL), in collaboration with G. Canalizo (U Hawaii, and LLNL), A. Stockton (U Hawaii), and M. S. Brotherton (NOAO) studied the  $z = 0.6344$  post-starburst quasar UN J1025-0040 using Keck imaging and spectroscopy. Previous observations had shown that the quasar has an extremely bright post starburst population of age 400 Myr. The new Keck data show that the quasar has also a nearby (4.2 arcseconds) companion galaxy at redshift  $z = 0.6341$ , with an estimated age of 800 Myr for the dominant stellar population. The companion appears to be interacting with the quasar host galaxy, and this interaction may have triggered both the starburst and the quasar activity in UN J1025-0040.

W. van Breugel (LLNL), in collaboration with colleagues from Leiden Observatory (J.D. Kurk, H.J.A. Rottgering, L. Pentericci, and G.K. Miley), C.L. Carilli (NRAO), H. Ford and T. Heckman (Johns Hopkins University), P. McCarthy (OCIW) and A. Moorwood (ESO) imaged the powerful radio galaxy PKS 1138-262 at  $z = 2.156$  and its surrounding 38 square arcminute field with the ESO Very Large Telescope in a broad band and a narrow band filter encompassing the redshifted Ly- $\alpha$  emission (Kurk *et al.* 2000). Approximately 50 objects were detected with rest equivalent widths larger than 20 Angstrom, as well as a luminous, very extended Ly- $\alpha$  halo around the radio source. If the radio galaxy is at the center of a forming cluster, as observations at other wavelengths suggest, the Ly- $\alpha$  emitting objects are candidate cluster galaxies at the redshift of the radio galaxy. Subsequent spectroscopic observations of these objects (Pentericci *et al.* 2000), also with the VLT, confirmed that 14 galaxies

and one QSO are at approximately the same distance as the radio galaxy. All galaxies have redshifts in the range  $2.14 < z < 2.18$ , centered around the redshift of the radio galaxy, and are within a projected physical distance of 1.5 Mpc from it. The velocity distribution suggests that there are two galaxy subgroups having velocity dispersions of 500 km/s and 300 km/s and a relative velocity of 1800 km/s. If these are virialized structures, the estimated dynamical masses for the subgroups are 9 and  $3 \times 10^{13}$  M(solar) respectively, implying a total mass for the structure of more than  $10^{14}$  M(solar). The observations strongly suggest that the structure of galaxies around PKS 1138-262 is a forming cluster.

W. van Breugel (LLNL), in collaboration with M. Kishimoto and R. Antonucci (UC Santa Barbara), A. Cimatti (Arcetri Observatory), T. Hurt (UC Santa Barbara), A. Dey (NOAO) and H. Spinrad (UC Berkeley) used UV spectropolarimetry and far-UV spectroscopy with the Faint Object Spectrograph onboard the Hubble Space Telescope (HST) to search for evidence of hidden quasars and determine the nature of scattering regions in two low-redshift narrow-line radio galaxies (Kishimoto *et al.* 2000). Spectropolarimetry of several Narrow Line Radio Galaxies (NLRGs) has shown that they have hidden quasars, as inferred from the presence of scattered, polarized broad permitted lines. Imaging polarimetry has shown that NLRGs, including the two observed targets, often have large scattering regions of a few kpc to 10 kpc scale. This poses a problem for understanding the nature of the scatterers in these radio galaxies. From the HST observations, when combined with previous optical/infrared polarimetry data, it was found that the scattering might be caused by opaque dust clouds in the NLRGs, and this would be a part of the reason for the apparently grey scattering. In high-redshift radio galaxies these opaque clouds could be the proto-galactic subunits which may be seen in HST images. However, one can not rule out the possibility of electron scattering, which could imply the existence of large gas masses surrounding these radio galaxies.

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 (Chen *et al.* 1999, Nature 398, 586) 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  $z = 1.51$  (Stern *et al.* 2000).

### 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. The Keck AO system routinely achieves resolutions of 0.04 arcseconds in H-band, the highest-resolution infrared imaging system in astronomical

use (Wizinowich *et al.* 2000). During 2000, LLNL engineers worked on understanding and improving Keck AO performance, in particular the deep AO point spread function for high-contrast imaging. The LLNL participation in the Keck AO effort is led by S. Olivier and C. Max.

LLNL also continued to refine the laser guide star (LGS) AO system on the 3-m Shane telescope at Lick Observatory. The Lick AO team is led by D. Gavel (LLNL). At 15-20 watts, this is the most powerful operational sodium laser beacon in the world, and has achieved the highest Strehl ratio (0.4) recorded for such a system. Improvements in 2000 focused on usability, improving the robustness of the Lick AO/LGS system to the point where it is an easily-operated facility-grade system, and reducing the manpower requirements for the laser system. In natural guide star (NGS) mode, the system requires a  $V < 13$  star within 30-40 arcseconds; in LGS mode, it requires a  $R < 17$  star within 60 arcseconds. Many improvements to the laser were based on similar modifications to the laser delivered for the Keck AO system, which is expected to be tested in 2001.

In November 2000 the Center for Adaptive Optics began operating at UC Santa Cruz under the NSF Science and Technology Program. LLNL is a major participant in this Center, with C. Max (LLNL) serving as the Center's Associate Director for Advanced Adaptive Optics Technology, and S. Olivier (LLNL) 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, H. Roe, and S. Martin (UC Berkeley), have been observing solar system objects at very high spatial resolution using the Keck AO system. During 2000 they observed and analyzed data from near-infrared observations of Saturn's largest moon Titan and the gas giant planets Uranus and Neptune.

Observations of Titan on 30 October 1999 showed a bright cloud band at 70 degrees latitude in two narrowband filters which probe the atmosphere above the tropopause. The feature was spatially unresolved in latitude and extended over all visible longitudes. Furthermore a broad haze band was seen, extending over approximately 60 degrees of latitude centered slightly south of Titan's equator. The AO system achieved a spatial resolution at 1.158 microns of 0.032 arcseconds, or 190 km on Titan. Mid-infrared Long Wavelength Spectrometer (LWS) images from September and November 1999 with a resolution of 0.25 arcseconds clearly show east-west and north-south structure across the disk of Titan; the emission is probably thermal, from high-altitude haze layers.

The LLNL / UC Berkeley group also observed Neptune several times during the year, a project which culminated in June 2000 with a large coordinated effort, along with A. Ghez (UCLA) and M. Brown (Caltech) to track infrared-bright features over a 20-day period. The images are spectacular, revealing narrow zonal bands at 3-4 degree latitude spacings within bright regions and near the equator. There are three zones of latitude which contain bright features along zonal bands. The dimmest zone is located in the North-

ern hemisphere and extends from 20 degrees N to 40 degrees N. There are two bright zones located in the Southern hemisphere which extend from 20 degrees S to 50 degrees S, and from 60 degrees S to 70 degrees S. The zone near the South pole, a recently quiet region, contains a bright tear drop shaped feature which may be related to the Westerly jet previously observed by Voyager at a similar latitude.

The planet Uranus was observed with the recently commissioned AO/NIRSPEC system (Adaptive Optics system with the Near-Infrared echelle Spectrograph) on June 17 and 18, 2000. With this system images and spectra can be taken simultaneously. Excellent images were obtained of Uranus' ring system. Inside of the Epsilon ring at least three more, 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. On the planet itself at least eight different cloud features can be detected, five of which are in the Northern hemisphere (the hemisphere which just came into sunlight after being in complete darkness for 40 years). Two features could be tracked over a 40-60 degree longitude range, and yield wind velocities of 175 +/- 35 m/s at a latitude of 30 degrees, and of 120 +/- 40 m/s at 40 degrees latitude. The data suggest that the wind profile is similar to that derived for Neptune, though at reduced velocities.

### 3.3 Extrasolar Planets

With the Keck AO system operational, it now becomes possible to directly detect 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 (UCLA) are beginning a large-scale search for such young planetary companions to field stars, with UCLA identifying new populations of young stars while LLNL works on improved techniques for high-contrast imaging. Adaptive Optics is currently the only technique that can detect planets in 20-100 AU orbits.

### 3.4 Active Galaxies and Starburst Systems

W. de Vries, W. van Breugel (LLNL), and A. Quirrenbach (UCSD), have begun a Keck AO imaging program of powerful radio galaxies and Ultraluminous Infrared Galaxies (ULIRGs). Observations of two radio galaxies and a ULIRG during a June 2000 NIRSPEC-AO run at the Keck telescope have provided unprecedented morphological resolution of components like nuclear dust-lanes, off-centered or binary nuclei, and merger induced starforming structures. All of these are key features in understanding galaxy formation and the onset of powerful radio emission. Furthermore, since the near-IR resolution of the AO images matches, or even surpasses, the optical resolution of HST, high resolution color images can be constructed by combining the AO and HST datasets. These maps provide an even better handle on off-nuclear starformation and obscuration properties of these merger induced structures. NIRSPEC-AO spectroscopic followup has been proposed to start a high resolution analysis

project of these features in particular. AO can provide the high spectroscopic and spatial resolution essential to this program, which will contribute significantly to our understanding of black hole mass distribution among radio galaxies, galaxy mergers, and the triggering of powerful radio emission.

#### 4. INSTRUMENTATION

V-Division has been developing advanced imaging Fourier transform spectrometers (IFTS) for ground and space-based astronomy. S. Blais-Ouellette, 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 (Univ. Washington), F. Grandmont (Bomem, Inc.), M. Abrams (ITT), and S. Morris (HIA).

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. 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 also developing both visible and mid-IR capability.

The present FTS design is potentially suitable for space-based instruments. It was built by Bomem 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. First observations using this instrument were conducted at the 3.5-meter Apache Point Observatory in April 2000. Engineering runs and initial science observations will continue into the coming year.

The 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, and 'quick-look' data inspection software. 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.

S. Labov, M. Frank, J. Ullom, A. Loshak, M. van den Berg (LLNL), S. Friedrich (LBNL, and LLNL), D. Chow, M. Cunningham, O. Drury, L.J. Hiller (UC Davis, and LLNL) and 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 resolu-

tion 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. 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 principal, resolving powers as high as 1000 may be obtainable in the X-ray band.

E. Wishnow, in collaboration with R. Wurtz and K. Cook (LLNL), completed the Long Wavelength Infrared Camera (LWIRC) program for which he is the P.I. 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. The camera was delivered to the observatory in Oct. 1999. Features of the camera include: chopping and nodding capability, very good stray light rejection, a very high dynamic range preamplifier/ADC system with high immunity to electronic noise, 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 and LLNL.

E. Wishnow (LLNL), H. Gush, M. Halpern, I. Ozier (University of British Columbia), are conducting studies of the collision-induced submillimeter spectra of low temperature gases. The initial studies of nitrogen-argon gas mixtures are pertinent to the interpretation of the spectrum of Titan. The studies are also of importance in the field of molecular physics and provide information on the nature of the intermolecular potential. The measurements will be conducted using a unique differential Michelson interferometer and dual-pipe cryogenic absorption cell. The studies use low pressure gas samples at temperatures between 78 and 90 K and cover the spectral range 3-25 wavenumbers (3000-400 microns).

W. van Breugel (LLNL) and J. Bland-Hawthorn (AAO) co-edited the proceedings of a major international conference on 'Imaging the Universe in Three Dimensions: Astrophysics with Advanced Multi-Wavelength Imaging Devices'. This conference was held under the auspices of LLNL, in Walnut Creek, California, from March 29 - April 1, 1999. The purpose was to bring together instrumentation experts and observers to discuss the new opportunities afforded by the new class of advanced multi-wavelength imaging instruments that are currently being designed for major ground-

and space-based observatories. The proceedings have been published in the *Astronomical Society of the Pacific Conference Series* Nr. 195. There were 18 invited review talks, covering scientific opportunities and instrumental challenges, 23 talks highlighting some of the first results obtained with 3-D instruments, 19 contributed talks, and 43 poster. The main topics covered by the science talks were related to galaxy formation and large scale structure, obscured galaxies, starbursts and AGN, outflows from stars, starbursts and active galaxies, and the evolution and environments of quasars. Nearly 90 papers are included in the proceedings, with more than 600 pages. The volume serves as an important reference work on advanced multiwavelength imaging.

## 5. LABORATORY ASTROPHYSICS

### 5.1 Planetary Interiors

R. Chau, M. Bastea, and W. J. Nellis (LLNL) have measured the electrical conductivities of oxygen, nitrogen, and water under conditions found deep within Neptune and Uranus. The electrical conductivities of both oxygen and nitrogen exhibit a transition from a non-metallic to metallic conductivity at 100 and 120 GPa, respectively. The behavior of oxygen and nitrogen are identical to that previously observed in hydrogen. Water was observed to be an ionic conductor and is likely fully dissociated. However, the conductivity of water was an order of magnitude less than that of hydrogen or oxygen. This suggests that chemical interactions between atomic species are very important at the high pressures and temperatures within the interiors of Uranus and Neptune.

### 5.2 Far-UV and X-ray Spectroscopy

Using the Livermore EBIT-II facility, P. Beiersdorfer, G. Brown, H. Chen, S. B. Utter and their collaborators M.-F. Gu, S. Kahn, D. Savin (Columbia University), and J. Lepson (UC Berkeley) continued their measurements to test the accuracy and completeness of spectral models of astrophysical plasmas. Addressing the controversy over the origin of the enhanced continuum emission in stellar coronae observed with the short-wavelength spectrometer aboard the Extreme Ultraviolet Explorer mission, they made detailed spectral measurements of the Fe VII - Fe XIV emission in the 60 to 140 wavelength region. They found that numerous weak lines from these charge states contribute to the continuum producing a considerable enhancement. None of the spectral models include the bulk of these lines. In the case of the Fe XIII, for example, standard spectral models reproduce less than 5% of the flux observed in the laboratory; some, such as the CHIANTI model, include none of the observed lines! For cool and medium temperature stars, such as alpha Cen, the failure to include the contributions from these lines in global spectral fits was shown to result in an unphysical apparent high continuum emission. A systematic set of short-wavelength extreme ultraviolet laboratory spectra from the Livermore EBIT-II facility is now available for all charge states of iron.

P. Beiersdorfer, G. Brown, H. Chen, S. B. Utter, and their collaborators M.-F. Gu, S. Kahn, and D. Savin from Columbia University extended their laboratory tests of the accuracy

of line excitation calculations to the  $n=4$  to  $n=2$  transitions in the L-shell spectra of Fe XXII and Fe XXIV. The contributions from direct electron-impact excitation, resonance excitation, radiative cascades, and blends with unresolved dielectronic satellite lines were carefully measured and compared with calculations. They found that most calculations reproduced the excitation data very well (within 10%). Moreover, they showed that resonance excitation, generally missing from spectral models, was relatively unimportant in all but very low-temperature situations. As a result, they concluded that excitation data from direct quantum mechanical calculations (i.e., distorted-wave or R-matrix calculations) is in reasonable shape. They found, however, that the wavelengths used in most models need to be adjusted to those obtained in the laboratory before a fit of high-resolution L-shell iron data from Chandra or XMM can be made.

P. Beiersdorfer, G. Brown, and H. Chen in collaboration with K. Boyce, K. Gendreau, J. Gygas, R. Kelley, C. Stahle, and A. Szymkowiak (Goddard Space Flight Center) implemented the XRS X-ray calorimeter at the EBIT-II facility. The XRS calorimeter had been developed at GSFC for the ASTRO-E mission. Its use on the EBIT-II added broadband X-ray measurement capabilities that complemented existing crystal and grating spectrometers. Laboratory astrophysics investigations included iron L-shell and K-shell emission surveys, spectral diagnostics of ionizing plasmas, and excitation cross section measurements. The measurements on EBIT-II also provided a test bed for developing XRS analysis tools useful for future space missions, as well as for assessing and validating the long-term stability of the XRS calorimeter and electronics.

E. Traebert, P. Beiersdorfer, H. Chen, S. Utter (LLNL), D. Savin (Columbia), C. Harris, P. Neill (University of Nevada Reno), and A. Smith (Morehouse College) performed measurements of the radiative transition rates of the coronal lines of Ar X, Ar XIV, and Ar XV. Contrary to earlier self-assessments that presumed that calculations of the radiative rates are only good to within 20-30%, rate calculations are reliable within 5%.

P. Beiersdorfer started a new project to measure X-ray line formation by charge exchange between highly charged ions from the solar or stellar winds and neutral gases from such sources as comets or the interstellar media. He and his collaborators G. Brown, H. Chen, S. Utter, K. Widmann (LLNL), C. Harris, P. Neill (University of Nevada Reno), L. Schweikhard (University of Mainz Germany), and R. Olson (University of Missouri Rolla) showed that the shape of the X-ray emission following charge exchange depends on the collision energy. This fact provides a new spectral diagnostic for determining, for example, the speed of solar wind ions interacting with cometary comae.

R. Heeter, M. Foord (LLNL), J. Bailey (Sandia Nat'l Lab - Albuquerque), M. Cuneo (Sandia), J. Emig, D. Liedahl, P. Springer, and R. Thoe have developed and conducted experiments on the photoionization equilibrium of iron at the Sandia Z facility. The experiments are designed to provide empirical benchmarks for photoionization models used to interpret Chandra and XMM X-ray spectra from accreting sources such as X-ray binaries and active galactic nuclei. A

comparison of the models finds it difficult to get agreement on the expected charge state balance. In the experiments, thin foils are heated and expanded by intense X-rays from the Z pinch. The pinch power, temperature, and spectrum are measured vs. time. Time-integrated and time-resolved absorption and emission spectra of the iron foils have been obtained. Detailed analysis of the data is underway.

E. Traebert, P. Beiersdorfer, H. Chen, S. Utter (LLNL), D. Savin (Columbia), C. Harris, P. Neill (University of Nevada Reno), and A. Smith (Morehouse College) performed measurements of the radiative transition rates of the coronal lines of Ar X, Ar XIV, and Ar XV. Contrary to earlier self-assessments that presumed that calculations of the radiative rates are only good to within 20-30%, Traebert and coworkers found that many rate calculations are reliable within 5%.

### 5.3 Laser Astrophysics Experiments

P. Drake (Univ. of Michigan), in collaboration with H. Robey, J. Kane, and B. Remington (LLNL), has been developing 4 experiments on the Omega laser at the Univ. of Rochester to address various issues of core-collapse supernova explosion hydrodynamics. Extensive observational evidence from core-collapse supernovae such as SN 1987A indicates that some form of large-scale hydrodynamic mixing is required to explain the resulting light curves, spectra, and velocities of the heavier elements produced by explosive nucleosynthesis near the core. High-resolution 2-D numerical simulations have been unable to reproduce these observations. In the experiments being developed by Drake and coworkers, a high intensity laser pulse from the Omega laser is used to drive a strong shock ( $M \gg 1$ ) into the target materials. The issues under investigation are interface coupling in a 3-layer configuration, planar vs. spherically divergent geometry, 2-D vs 3-D instability evolution, and multimode vs. single-mode perturbation growth and saturation. Numerical simulations generally were found to provide reasonable agreement with the experiments, which suggests that discrepancies with SN observations may be input related.

P. Drake (Univ. of Michigan), in collaboration with T. Perry (LLNL), also initiated an effort to develop a radiative-shock testbed relevant to supernova remnants (SNR). 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 designed the laser experiment, developed the point projection absorption spectroscopy diagnostic, and made the first attempts at this difficult experiment on Omega. The development work will continue throughout the coming year.

R.I. Klein (LLNL, and UC Berkeley) in collaboration with T. Perry (LLNL), and H. Robey (LLNL) conducted a new set of laser experiments on the OMEGA laser at Rochester NY investigating the evolution of a high density sphere embedded in a low density medium after the passage of a strong shock wave, thereby emulating the interaction of a supernova shock with an interstellar cloud. The OMEGA laser was utilized to generate a strong (Mach 10) shock wave which traveled along a miniature beryllium shock tube filled with a low density plastic emulating the interstellar medium (ISM). Embedded in the plastic was a copper mi-

croisphere emulating the interstellar cloud. Its morphology and evolution as well as the shock wave trajectory were diagnosed via both face-on and side-on radiography. They carried out the experiment to several cloud crushing times and compared the results to detailed three dimensional radiation hydrodynamic simulations performed by Klein in collaboration with M. Marinak (LLNL). It showed the development of the Vortex bending mode instability that they had predicted with 3-D calculations. The significance of the vortex ring instability is that it may play a key role in the destruction of interstellar clouds by supernova remnants. The experiment may shed light on the mechanism for mixing of intercloud gas with interstellar cloud material, and also provides a powerful validation test for complex 3-D codes.

R. Kodama, H. Azechi, and K. Shigemori (Osaka Univ.), in collaboration with B. Remington and his team at LLNL, have carried out a high Mach number, radiative jet experiment using the high power Gekko-12 laser at Osaka Univ. Although Herbig-Haro (HH) astrophysical jets, such as the well-known HH47, have emerged as "Galactic laboratories" for the study of radiative hydrodynamics, it is desirable to produce similar radiative jets in the laboratory where the underlying physics can be diagnosed in more detail up close. In the Gekko campaign, the "Z" of the jet was varied using targets of Au, Fe, Al, and CH. The high "Z" jets (Au, Fe) radiatively collapsed on axis, but the low "Z" jets (Al, CH) did not. These data will prove invaluable for the benchmarking of radiative hydrodynamics, astrophysics codes and reinforce the utility of high energy lasers to the astrophysics community.

M. Pound (Univ. of Maryland), in collaboration with D. Ryutov, J. Kane, and B. Remington of LLNL, have started to look at 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 photoevaporates and accelerates 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. In the cometary model, the Pillars consist of gas swept behind dense regions of the cloud impacted by supersonic ionization fronts. Theoretical and numerical evaluations of these models, implications for observations, and possible scaled verification experiments using intense lasers are being assessed.

D. Ryutov (LLNL) developed the theoretical criteria behind scaling astrophysics into the laboratory. His assessment looked at issues such as the hydrodynamics of core-collapse supernovae explosions; young supernova remnants; galactic jets; the formation of fine structures in late supernova remnants by instabilities; and the ablatively driven evolution of molecular clouds illuminated by nearby bright stars. 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 many years. It was demonstrated that if dissipative

processes such as viscosity and Joule heating are subdominant in both systems, and if the matter behaves as a polytropic gas, the equations of ideal MHD apply. In this case, there exists a broad hydrodynamic similarity (the ‘‘Euler similarity’’) that allows a direct scaling of laboratory results to astrophysical phenomena.

K. Shigemori (Osaka Univ.) and E. Liang (Rice Univ.) have carried out experiments to create a radiative blast wave in the laboratory, using the Falcon laser at LLNL. The experiments were done in collaboration with T. Ditmire, J. Edwards, and B. Remington at LLNL. This work is relevant to supernova-remnant and interstellar medium dynamics. Gas cluster targets (N<sub>2</sub>, Ar, Xe) are irradiated by a Ti: sapphire laser (pulse duration: 30 fs, laser energy: 10-100 mJ). The blast wave propagation was measured by the Michelson interferometry, and an ionization precursor due to radiative preheat was observed. This radiative precursor was more significant for higher atomic-number gas.

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