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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 Physics Directorate and, on a part-time basis, by about 22 other scientists who have additional responsibilities in the large LLNL programs with a growing emphasis on high energy laser experiments 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. C. Alcock is the Director of the LLNL branch of IGPP, which is organized into two centers led by K. Cook (Astrophysics) and F. Ryerson (Geosciences). The goals of the IGPP branch at LLNL are to make available to UC researchers some of LLNL's unique facilities and expertise, and to provide a forum for seminars, workshops, etc. This year, IGPP awarded small research grants totaling more than $606,700 to UC campus faculty and staff members, enabling 23 collaborative projects.

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

The Physics 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 Physics 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, D. Dearborn, M. Frank, S. Labov, D. Liedahl, C. Mauche, H.-S. Park, R. Porrata, J. Wilson, E. Wishnow, R. Wurtz, and K. Ziock make up the core of the Astrophysics Group. In addition, the Astrophysics Group includes several postdoctoral fellows and graduate students who work on astrophysics-related projects.

2. RESEARCH

2.1 Dark Matter

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, M. Geha, S. Marshall, C. Nelson, and P. Popowski (LLNL); R. Allsman, T. Axelrod, A. Drake, K. Freeman, and B. Peterson (Mt. Stromlo Obs., Australia); A. Becker, C. Stubbs, and A. Tomaney (CfPA at U/Washington); K. Griest and Th. Vandehei (CfPA at UC San Diego); D. Alves (STScI); D. Bennett (Notre Dame); M. Lehner (U/Sheffield); D. Minniti (P. Univ. 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

$$10^{-7}M_{sun} < M < 10M_{sun}.$$

If the dark matter consists of MACHOs, it will occasionally magnify light from extragalactic stars by the gravitational lens 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 (it is achromatic). Unambiguous recognition of microlensing requires adequate data points on the light curve (10) and measurements in at least two filter bands. To detect events, one must monitor millions of stars for several years. The experiment has been operating for seven years and is in its final year of collecting data.

The MACHO Project uses the 130-cm reflecting telescope of the Mt. Stromlo Observatory, near Canberra, Australia. Operating at prime focus with an innovative optical system gives a field of view 1 deg in diameter. A dichroic filter is used for simultaneous imaging in a blue and a red spectral band, doubling the effective exposure rate. The Project has been monitoring fields in the Large and Small Magellanic Clouds (satellite galaxies of the Milky Way) as well as fields toward the center of the Milky Way. The Project has accumulated almost 7 TBytes of image data and about 600

Gbytes of photometry on about 70 million stars. Data is reduced in near real time, and microlensing events are often identified well before their peak.

The Project sends out alert announcements to the world, which are also posted on its web site (http://darkstar.astro.washington.edu/). These alert announcements are used by different groups throughout the world to search for planets and to study ongoing microlensing events in detail. Planets can be detected via microlensing when they orbit the lensing object, and most of the lenses detected toward the center of the Milky Way are normal stars. Over 400 microlensing events have been recorded. Analysis of these events shows that planets and brown dwarfs are not significant components of the dark matter, but that ancient white dwarfs might be.

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.

The large number of microlensing events toward the bulge has forced a revision in our view of the Milky Way's structure. It is now thought most likely that we live in a strongly barred spiral galaxy. The microlensing detected by the Project toward the Large Magellanic Cloud suggests that the halo of the Milky Way has a significant MACHO component. If the halo of our galaxy is assumed to be a relatively 'standard' halo, the MACHOs comprise about 70% of the dark matter and have masses of about 0.7 M_{sun}. This result has far-reaching consequences for the formation of structure in the Universe.

The Project has also detected two microlensing events toward the Small Magellanic Cloud. Both events were discovered by the alert system and were studied in detail by groups around the world. The MACHO Project alerted the world that the second event was likely to be a binary lens-caustic crossing event and predicted the caustic-crossing time. This led to an intense observing program around the world. Analysis of this non-standard microlensing event has placed the binary lens in the Small Magellanic Cloud itself, along with the source star. Major microlensing surveys conducted a joint analysis using all the available data.

The MACHO collaboration has been carrying out difference image analysis (DIA) since 1996 with the aim of increasing the sensitivity to the detection of gravitational microlensing. The DIA technique was applied to galactic bulge images in one field. It showed how this significantly increases the number of detected lensing events, by removing the positional dependence of traditional photometry schemes and lowering the microlensing event detection threshold. This technique, unlike PSF photometry, gives the unblended colors and positions of the microlensing source stars. The MACHO collaboration presented a set of criteria for selecting microlensing events from objects discovered with this technique.

MACHO also presented consecutive papers about variable stars in the Magellanic Clouds and the color-magnitude diagram of the field stars. These investigations put constraints on the star formation rate in the LMC and allowed to explore the physics of pulsation of fundamental and first overtone variables. One of the important practical advances was a completion of the photometric calibration of data in the LMC. The absolute calibration of photometry is of secondary importance to the microlensing studies, but essential for the variable star research.

The light curves of 21 gravitational microlensing events have been presented that are likely examples of lensing by binary systems. At least 14 of these 21 events exhibit strong (caustic) features, and 4 of the events are well fit with lensing by large mass ratio (brown dwarf or planetary) systems, although these f its are not necessarily unique. The total binary event rate is roughly consistent with predictions based upon our knowledge of the properties of binary stars. Towards the Galactic bulge, a ratio of caustic crossing to non-caustic crossing binary lensing events of 12:4 is found. This suggests significant incompleteness in the ability to detect and characterize non-caustic crossing binary lensing. The distribution of mass ratios for these binary lenses appears relatively flat. It is also possible to reliably measure source-face crossing times in 4 of the bulge caustic crossing events, and recover from them a distribution of lens proper motions, masses, and distances consistent with a population of Galactic bulge lenses at a distance of 7 ± 1 kpc. This analysis yields 2 systems with companions of 0.05 M_{sun}.

In related work P. Popowski argued that two unexpected results in the local Universe are connected: 1) The anomalous intrinsic $(V - I)_0$ colors of the clump giants and RR Lyrae stars in the Galactic center, and 2) the very short distances to the Magellanic Clouds (LMC, SMC) as inferred from clump giants. The $(V - I)_0$ anomaly is partially resolved by using the photometry from the phase-II of the Optical Gravitational Lensing Experiment (OGLE) rather than phase-I. The need for V- or I-magnitude-based change in the bulge $(V - I)_0$ is one option to explain the remaining color discrepancy. Such change may originate in a coefficient of selective extinction $A_V/E(V - I)$ smaller than typically assumed. Application of the $(V - I)_0$ correction (independent of its source) doubles the slope of the absolute magnitude – metallicity relation for clump giants, so that $M_I(RC) = -0.23 + 0.19[\mathrm{Fe/H}]$. Consequently, the estimates of the clump distances to the LMC and SMC are affected. The distance to the LMC becomes $\mu_{LMC} = 18.27 \pm 0.07$. The distance modulus to the SMC increases to $\mu_{SMC} = 18.77 \pm 0.08$. Popowski concluded that a more comprehensive assessment of the metallicity effect on $M_I(RC)$ is needed.

2.2 Normal Galaxies and Galaxy Formation

M. Gregg (UC Davis, and LLNL) and M. West (U. St. Mary's Halifax) reported the discovery of several large low surface brightness structures in the Coma galaxy cluster. The LSB features were found in deep broad band CCD images obtained with the Kitt Peak Burrell Schmidt telescope. The most striking is a plume-like feature about 130 kpc in length and 10-20 kpc long. These objects are interpreted as tidally disrupted galaxies or parts of galaxies which will disperse in a few dynamical timescales, augmenting the intracluster population of stars and gas or augmenting the haloes of the giant ellipticals which dominate the center of the cluster. If this is a typical moment in the history of Coma, such disrupted objects can account for most of the light in the haloes of the central galaxies.

M. Gregg (UC Davis, and LLNL) and D. Minniti (U. Catòlica, Chile, and LLNL), in collaboration with H. Ferguson (STScI), N. Tanvir (IofA, Cambridge), R. Catchpole (RGO), and S. Hughes (IofA, Cambridge) used the Hubble Space Telescope infrared camera (NICMOS) to obtain J and H band images of the halo of NGC3379, the nearest prototypical elliptical. The images clearly resolve individual red giants, permitting the first ever color-magnitude diagram of stars in a completely normal, luminous elliptical galaxy. The results will be used to estimate the metallicity of the halo of NGC3379, providing constraints for modeling the stellar population and chemical evolution of elliptical galaxies. By dividing the imaging into two epochs several months apart, the images have also detected a variable stars which may be indicative of an intermediate age population.

With D.N.C. Lin (UCSC), S. Murray is investigating the evolution of the gas phases in protogalaxies. Collisions or infall lead naturally to a hot phase of gas, at the virial temperature of the system. Overdense regions, however, are able to cool to below 10,000 K, forming a warm phase. In the absence of sufficient UV flux, primarily from hot stars, the warm gas cools rapidly to below 100 K, forming cold, dense clouds which are the primary sites of star formation. Lin and Murray have begun by performing one-dimensional hydrodynamic models of the evolution of the warm and hot phases. The hot phase is heated by settling of the warm clouds into the gravitational potential of the galaxy, and cools both by bremsstrahlung emission and by conduction into the warm clouds. The warm clouds are cooled by line emission, and heated primarily by UV radiation from stars, which are assumed to form at a rate necessary to prevent runaway cooling and star formation in the warm phase. The models find pressure and density distributions consistent with those inferred for the conditions under which globular clusters formed, and stellar distributions similar to those observed in galactic spheroids. The densities of the hot gas of the models are low, consistent with the observed absence of hot gas in galactic halos at large redshifts.

2.3 Clusters of Galaxies

S.A. Stanford (UC Davis, and LLNL) has been working on a near-IR mosaic made with HST/NICMOS of the Hubble Deep Field. In collaboration with M. Dickinson (STScI), he has identified a morphologically selected sample of early-type galaxies reaching to faint magnitudes and high redshifts. The color, luminosity, and redshift distributions of this sample has been compared with the predictions of passive luminosity evolution models for standard cosmologies. These models provide poor fits to the properties of the early-type galaxies, indicating that elliptical galaxies in HDF may not have formed monolithically at high redshift. An alternative theory based on hierarchical merging and cold dark matter scenario for structure formation is being investigated with R. Somerville (Cambridge University).

S.A. Stanford (UC Davis, and LLNL), P. Rosati (ESO), and P. Eisenhardt (JPL) have been developing a sample of high redshift galaxy clusters. This sample begins with candidate X-ray sources selected from Rosat archival pointings with the PSPC instrument. These sources are then identified either in the optical or in the near-IR. The recent work has concentrated on the faintest targets not yet identified. Followup spectroscopy at Keck and at the VLT have resulted in the discovery two new $z > 1$ clusters in the past year, as well as two other high redshift clusters. These clusters are being studied for clues to the formation and evolution of elliptical galaxies in clusters, and to provide constraints on the formation of large scale structure at high redshifts.

S.A. Stanford (UC Davis, and LLNL), P. Eisenhardt (JPL), R. Elston (UF-Gainesville), H. Spinrad (UC Berkeley), and D. Stern (UC Berkeley, and JPL) continued work on obtaining redshifts for a $K < 20$ sample of galaxies from their field galaxy survey. This covers 100 square arcminutes and includes approximately 1700 objects down to $K = 20$. The spectroscopic work is being carried out at the Keck II telescope. Early results from one of the four fields in the survey indicates that a larger fraction of galaxies are at $z > 1$ than had been found in previous smaller surveys.

2.4 Active Galactic Nuclei and Quasars

N. Arav, in collaboration with R.H. Becker (UC Davis, and LLNL), S.A. Laurent-Muehleisen, M.D. Gregg (UC Davis, and LLNL), R.L. White (STScI) and M. de Kool (ANU, Australia) have studied the broad absorption line (BAL) quasi-stellar object (QSO) 1603+3002 using deep observations with the High Resolution Spectrograph (HIRES) at the Keck I telescope. They find that the depth and shape of the BAL emission lines in BALQSO 1603 +3002 are determined largely by the fraction of the emitting source which is covered by the BAL flow. In addition, the observed depth of the BALs is poorly correlated with their real optical depth. The implication of this result is that abundance studies based on direct extraction of column densities from the depth of the absorption troughs are unreliable. This conclusion is based on analysis of unblended absorption features of two lines from the same ion (in this case the Si IV doublet), which allows unambiguous separation of covering factor and optical depth effects. The complex morphology of the covering factor as a function of velocity suggests that the BALs are produced by several physically separated outflows. The covering factor is ion dependent in both depth and velocity width. They also find evidence that in BALQSO 1603 +3002 the flow does not cover the broad emission line region.

R. Becker together with M. Gregg and S.A. Laurent-Muehleisen (UC Davis, and LLNL) continued the FIRST survey imaging of the radio sky at 1400 MHz. Images and a source catalog have now been released for 6000 sq deg of sky. A quasar survey (FIRST Bright Quasar Survey - FBQS) of the initial 3000 sq deg of sky covered has been published which presents approximately 500 newly discovered quasars.

Highlights of the FBQS which have appeared in separate publications include the discovery of a new binary quasar system and a detailed spectral study of a radio-selected BAL quasar. Programs are in progress to search for gravitationally lensed quasars using HST, the VLA, and Keck Observatory.

M.S. Brotherton (LLNL, and NOAO), with W. van Breugel (LLNL), A. Stanford (UC Davis, and LLNL), R.J. Smith (MSSSO, Australia), B.J. Boyle (AAO, Australia), L. Miller (Oxford Univ., U.K.), T. Shanks (Durham Univ., U.K.), S.M. Croom (Imperial College, London, U.K.) and A.V. Filippenko (UCB) reported the discovery of a spectacular ‘‘post-starburst quasar,’’ UN J1025-0040 at z=0.634. The optical spectrum is a chimera, displaying broad Mg II line emission and strong blue continuum characteristic of quasars, but is dominated in the red by a large Balmer jump and prominent high-order Balmer absorption lines indicative of a substantial young stellar population at similar redshift. Stellar synthesis population models show that the stellar component is consistent with a massive, 400 Myr old instantaneous starburst. Most of the light from the quasar is unresolved, the majority of which is expected to be emitted by the starburst. While starbursts have been previously associated with quasars, no quasar ever before has been seen with such an extremely luminous young stellar population.

S.A. Laurent-Muehleisen (UC Davis, and LLNL) continued her work on the identification and study of BL Lacertae Objects. BL Lacs are thought to be relativistically beamed versions of normal low luminosity radio galaxies. In collaboration with E.D. Feigelson (Penn State) and W. Brinkmann (MPE, Germany), and based on a correlation of the 1990 ROSAT All-Sky X-ray Survey and 1987 Green Bank radio catalogs, she has constructed a sample of 118 BL Lacs, the largest sample ever created from one survey. These ‘‘RGB’’ BL Lacs have been shown to exhibit properties intermediate between the previously disparate subclasses of High and Low energy peaked BL Lacs (HBLs and LBLs, respectively). Because this sample bridges the gap between LBLs and HBLs, it is ideal for constraining BL Lac unification models. Followup work on the optical properties continue in collaboration with L. Takalo, A. Silanpaa, K. Nilsson and T. Pursimo (all at Tuorla Observatory, Finland) as well as T. Rector (NOAO).

S.A. Laurent-Muehleisen is also continuing a study in collaboration with R. Becker, M.D. Gregg (UC Davis, and LLNL) and M. Brotherton (LLNL, and NOAO) on the identification of quasars in the VLA's FIRST (Faint Images of the Radio Sky at Twenty Centimeters) survey. The survey has produced a sample of over 600 radio-selected quasars, many of which are intermediate in their radio-loudness properties. In addition, she has begun a study of the multiwavelength properties of BL Lacs which have been serendipitously discovered in this quasar search. Also in collaboration with W. Brinkmann (MPE, Germany), S.A. Laurent-Muehleisen is in the process of completing a large program to spectroscopically identify FIRST sources with X-ray counterparts in the ROSAT All-Sky Survey. The sample includes many quasars, starburst, Seyfert and radio galaxies in addition to some BL Lacs and nearby early type galaxies.

S.A. Laurent-Muehleisen (UC Davis, and LLNL) has continued her collaboration with C.M. Urry (STScI) and G. Fossati (UC San Diego) to create a large, deep sample of radio-selected blazars. This sample is based on the FIRST 20 cm and Green Bank 6 cm surveys and will produce a sample over an order of magnitude deeper than any previous flat spectrum blazar survey. This sample will be used to study the relationship between Flat Spectrum Radio Quasars and BL Lacs and to also investigate the long standing problem of which flavor of BL Lac (HBLs vs. LBLs) is intrinsically more numerous, a questions whose answer is currently uncertain by two orders of magnitude.

M.D. Lehnert (MPE, Germany), W. van Breugel (LLNL), T. Heckman (JHU) and G.K. Miley (Leiden Observatory, The Netherlands) studied the rest-frame UV and Ly-a images of spatially-resolved structures (‘‘hosts’’) around five high-redshift radio-loud quasars with the HST WFPC2 camera. The quasars were imaged with the PC1 through the F555W (‘V’-band) filter and at rest-frame Ly-a using appropriately chosen narrow-band filters with the WFC2. It was found that all five quasars are extended and their hosts contained significant fractions of the total continuum and Ly-a flux. The rest-frame UV luminosities of the hosts are comparable to those of luminous radio galaxies at similar redshifts and a factor 10 higher than both radio-quiet field galaxies and the most UV-luminous low redshift starburst galaxies. To generate the Ly-a luminosities of the hosts would require roughly a few percent of the total observed ionizing luminosity of the quasar. The UV continuum morphologies of the hosts appear complex and knotty at the relatively high surface brightness levels of the exposures. They show good alignment between the extended Ly-a emission and the radio sources, strong evidence for jet-cloud interactions in two cases, again resembling radio galaxies, and what is possibly the most luminous radio-UV synchrotron jet in one of the hosts at z = 2.110. The observations suggest that the host galaxies of radio-loud steep spectrum quasars are similar to those of radio galaxies and strengthen previous conclusions based on ground-based data that both types of objects are probably members of the same parent population.

H.D. Tran (LLNL, and JHU), M.S. Brotherton (LLNL, and NOAO), S.A. Stanford (LLNL, and UC Davis), W. van Breugel (LLNL), A. Dey (NOAO), D. Stern (UC Berkeley, and JPL), and R. Antonucci (UC Santa Barbara) carried out a spectropolarimetric search for hidden broad-line quasars in three ultraluminous infrared galaxies (ULIRGs) discovered in the positional correlations between sources detected in deep radio surveys and the IRAS Faint Source Catalog. Only the high-ionization Seyfert 2 galaxy TF J1736+1122 is highly polarized, displaying a broad-line spectrum visible in polarized light. The other two objects, TF J1020+6436 and FF J1614+3234, display spectra dominated by a population of young (A-type) stars similar to those of ‘E + A’ galaxies. They are unpolarized, showing no sign of hidden broad-line regions. The presence of young starburst components in all three galaxies indicates that the ULIRG phenomenon encompasses both AGN and starburst activity, but the most energetic ULIRGs do not necessarily harbor ‘buried quasars’. They find that a luminous infrared galaxy is most likely to host an obscured quasar if it exhibits a high-ionization spectrum typical of a 'classic' Seyfert 2 galaxy with little or no Balmer absorption lines, is 'ultraluminous', and has a 'warm' IR color. The detection of hidden quasars in this group but not in the low-ionization, starburst-dominated UL-IRGs (classified as LINERs or H II galaxies) may indicate an evolutionary connection, with the latter being found in younger systems.

2.5 Radio Galaxies

G.V. Bicknell, R.S. Sutherland (MSSSO, Australia), W. van Breugel (LLNL), M. Dopita (MSSSO, Australia), A. Dey (NOAO) and G.K. Miley (Leiden Observatory, The Netherlands) made a detailed study of the high redshift radio galaxy 4C41.17 using HST imaging and deep Keck spectroscopy. It was found that nuclear photoionization is not responsible for the excitation of the emission line clouds along the axis of the radio source and a jet-cloud interaction model is constructed to explain the major features revealed by the detailed radio, optical and spectroscopic data. The interaction of a high-powered jet with a dense cloud in the halo of 4C41.17 is thought to produce shock-excited emission-line nebulosity and induces star formation. The emission line ratios and luminosity emanating from the shock show that the pre-shock density in the line-emitting cloud is high enough that shock-initiated star formation could proceed on a timescale well within the estimated dynamical age of the radio source. The implied baryonic mass of the cloud is high and implies that Milky Way size condensations existed in the environments of forming radio galaxies at a redshift of 3.8. The interpretation of the data provides a physical basis for the alignment of the radio, emission-line and UV continuum images in some of the highest redshift radio galaxies and the analysis may form a basis for the calculation of densities and cloud masses in other high redshift radio galaxies.

Graduate student C. De Breuck (LLNL, and Leiden Observatory), in collaboration with W. van Breugel (LLNL), D. Minniti (Universidad Catolica, Chile) G. Miley, Huub Röttgering (Leiden Observatory, The Netherlands), S. A. Stanford (UC Davis, and LLNL), and C. Carilli (NRAO) have studied the first $z > 4$ radio galaxy discovered in the southern hemisphere at optical, infrared and radio wavelengths using the VLT Antu telescope, Keck I, and the Very Large Array. TN J1338 − 194 at $z = 4.11$ was found to be one of the most luminous Ly-a objects in its class. Its Ly-a emission and rest–frame optical emission appear co–spatial with the brightest radio hotspot of this very asymmetric radio source, suggesting extremely strong interaction with dense ambient clouds. The Ly-a emission is spatially extended by $\sim 4''$, has an enormous rest–frame equivalent width, $W_\lambda^{rest} = 210 \pm 50$ Å, and has a spectral profile that is very asymmetric with a deficit towards the blue. This blue-ward asymmetry is interpreted as being due to absorption of the Ly-a photons by cold gas in a turbulent halo surrounding the radio galaxy and inferred neutral hydrogen column density is shown to be in the range $3.5 - 13 \times 10^{19}$ cm^{-2}. The two-dimensional spectrum indicates that the extent of the absorbing gas is comparable (or even larger) than the $4''$ (30 kpc) Ly-a emitting region. The VLT observations also detect the continuum flux both blue-ward and red-ward of the Ly-a emission, allowing us to measure the Ly-a forest continuum break and the Lyman limit. They measure a continuum break $D_A = 0.37 \pm 0.1$, which is ~ 0.2 lower than the values found for quasars at this redshift. This difference may be due to a bias towards large D_A values which are introduced in high–redshift quasar samples that are selected on the basis of specific optical colors. If such a bias would exist in optically selected quasars, – and even in samples of Lyman break galaxies –, then the space density of both classes of object will be underestimated. Furthermore, the average H-I column density along cosmological lines of sight as determined using quasar absorption lines would be overestimated. Because of their radio-based selection, they argue that $z > 4$ radio galaxies are excellent objects for investigating D_A statistics.

P.P. Papadopoulos, H.J.A. Rottgering, P.P. van der Werf (Leiden Observatory, The Netherlands), S. Guilloteau (IRAM, France), A. Omont (IAP, France), W.van Breugel (LLNL), and R.P.J. Tilanus (JAC, Hawaii) discovered sub-mm emission from dust and CO line emission in the two distant radio galaxies 4C 60.07 (z = 3.79) and 6C 1909+722 (z = 3.53). The estimated molecular gas masses and FIR luminosities are very large, suggesting the presence of major starbursts. The observed large velocity widths (500 km/s) are characteristic of mergers. In the case of 4C 60.07 the CO emission extends over 30 kpc and spans a velocity range of 1000 km/s. The extraordinary morphology of the CO emission in this object suggests that it is not just a scaled-up version of a local Ultra Luminous Infrared Galaxy, but may be a forming massive elliptical. The effects of the excitation conditions on starburst environments are discussed and it is concluded that high excitation CO lines can be significantly weakened, hindering their detection even in the presence of substantial molecular gas masses.

W. van Breugel (LLNL), in collaboration with C. De Breuck (LLNL, and Leiden Observatory, The Netherlands), S.A. Stanford (LLNL, and UC Davis), Daniel Stern (UC Berkeley, and JPL), Huub Rottgering and George Miley (Leiden Observatory, The Netherlands) discovered the most distant known AGN, the radio galaxy TN J0924 − 2201 at z = 5.19. The radio source was selected from a new sample of ultra-steep spectrum (USS) sources, has an extreme radio spectral index and is identified at near-IR wavelengths with a very faint K = 21.3 object. Spectroscopic observations show a single emission line at 7530 A which is identified as Ly-a. The K-band image, sampling rest frame U-band, shows a multi-component, radio-aligned morphology, typical of lower-redshift radio galaxies. TN J0924 − 2201 extends the near-IR Hubble relation for powerful radio galaxies to $z > 5$, and is consistent with models of massive galaxies forming at even higher redshifts.

W. van Breugel (LLNL) and A.S. Stanford (UC Davis, and LLNL), with I. King (chair), M. Barnato, A. Bunker, and D. Stern (UC Berkeley) formed the Local Organizing Committee which organized a successful international conference 'The Hy-redshift Universe: Galaxy Formation and Evolution at High Redshift', which was held at the International House of the University of California, Berkeley, from June 21–24, 1999. The purpose was to celebrate the research interests of Hyron Spinrad for his 65th birthday. The meeting was attended by 160 participants, including most of Hy's collaborators and former students, as well as colleagues from all over the world. A. Bunker (UC Berkeley, and IoA Cambridge) and W. van Breugel (LLNL) co-edited the proceedings for this meeting which will be published in the Astronomical Society of the Pacific Conference Series. There were 43 invited review talks, 41 of which are included in this proceedings, giving a comprehensive snapshot of this field as of June 1999. In addition to these reviews, there were 46 contributed poster papers, which also appear in this volume.

2.6 Gamma Ray Bursts

S. Marshall (LLNL) is collaborating with C. Akerlof, R. Kehoe, B. Lee, and T. Mckay (U/Michigan); R. Balsano, J. Bloch, D. Casperson, S. Fletcher, G. Gisler, J. Hills, W. Priedhorsky, J. Szymanski and J. Wren (LANL) on ROTSE (Robotic Optical Transient Search Experiment) collaboration. ROTSE's primary goal is to search for prompt optical counterparts to gamma-ray bursts (GRB). The first phase of this project, ROTSE-I, comprises a 2x2 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 maginitude of 14.5. The second phase, (ROTSE-II), consists of two 0.45 m aperture telescopes with f/1.9 optics imaging to a cooled CCD camera. For 10 second exposures, the 2 degree field of view will be used to scan the BATSE error box in 16 minutes to a limiting visual magnitude of 17. More accurate initial coordinates will permit faster scans or deeper images. ROTSE-II has begun automated operation during the fall of 1999.

G. Mathews(U Notre Dame), J. Salmonson and J. Wilson have completed a model for gamma ray bursts based on the compression of neutron stars in binaries as the primary source of energy. The model is calculated using the following sequence of computer programs: the compressional heating is calculated with a three dimensional general relativistic program, the subsequent production of a electron-positron pair plasma via neutrino pair annihilation is calculated with a one dimensional general relativistic neutrino transport hydrodynamic program, and the expansion of the pair plasma into the interstellar medium is then calculated with a one-dimensional relativistic hydrodynamic program. The shock wave in the interstellar medium is assumed to be a magnetic field dominated collisionless shock. The gamma ray burst resulting from this model has an gamma ray energy of 10^{52} ergs, a time duration of a few tens of seconds, and a peak in the photon spectrum at about 100Kev. The model reproduces the 'smooth' gamma ray bursts well.

2.7 Laser Astrophysics Experiments

D. Arnett from the University of Arizona and Paul Drake from University of Michigan continue their to develop experiments using intense lasers to experimentally answer specific questions about hydrodynamic instabilities, in particular the Rayleigh- Taylor (RT) instability, as is relevant to the evolution of core-collapse supernovae (SNe). In particular, the high velocities of the core elements Ni, Co, and Fe in SN1987A are still unexplained (3000 km/s observed, versus predictions of about half that), and may have a bearing on the observed light curve. In collaboration with B.A. Remington and his team from LLNL, the group has carried out a series of experiments on the Nova laser at LLNL and has started experiments on the Omega laser at Rochester University to test the hydrodynamics of the supernova code PROMETHEUS. Simulations of SN1987A using PROMETHEUS suggest deep nonlinear hydrodynamic mixing of the core elements outwards through the He and H layers. Several supernova (SN) hydrodynamics experiments were carried out on the Nova laser, and new experiments are in progress on the Omega laser. On Nova, planar 2-layer experiments have been completed, and are described in several papers. The scaling was developed in a theoretical paper addressing the validity and limitations of laser-based laboratory experiments for supernova research. The result of the derived scale transformation is that accelerations of 10^{10} g_o (from the laser experiment) scale to 10 g_o for the SN, lengths of 100 micron scale to 10^{12} cm, and times of 10 nanosec scale to 10,000 sec. The group is now focusing on making their experiments more ''star like.'' New planar experiments have been carried out on 3-layer packages to simulate the 3-layer nature (core-He-H) of a typical SN progenitor. A cylindrically divergent experiment was done on Nova, and is shown in the figure below at the right. The times correspond to 35, 45, 55, and 75 ns. Compared to the SN (image on the left), the spatial scales differ by 14 orders of magnitude and the time scales differ by 12 orders of magnitude. Nevertheless, the hydrodynamic similarity is striking. Also, spherically divergent, 2-layer experiments are being developed on the Omega laser, to address the issue of spherical geometry on deep nonlinear hydrodynamic instabilities. The long-range goal of this work is to enhance our understanding of the deep nonlinear hydrodynamics of core-collapse supernovae. The results may help explain anomalies in the observed light curve from SN1987A and other SNe.

R. Klein (LLNL, and UC Berkeley), T. Perry and K. Budil (LLNL) performed a series of Nova laser experiments investigating the evolution of a high density sphere embedded in a low density medium after the passage of a strong shock wave, thereby emulating a supernova shock-cloud interaction. The Nova laser was utilized to generate a strong (Mach 10) shock wave which traveled along a miniature beryllium shock tube, 750 B5m in diameter, filled with a low-density plastic emulating the ISM. Embedded in the plastic was a copper microsphere (100 micron in diameter) emulating the interstellar cloud. Its morphology, evolution as well as the shock wave trajectory were diagnosed via face-on radiography. They carried out the experiment to several cloud crushing times and compared the results to detailed two and three dimensional radiation hydrodynamic simulations using both arbitrary Lagrangian and Eulerian hydrodynamics (ALE) as well as high resolution AMR hydrodynamics. They investigated the key hydrodynamic instabilities instrumental in destroying the cloud and showed the importance of inherently three dimensional instabilities such as the Widnall vortex ring instability and their role in cloud evolution. They studied the relationship of these new experiments and calculations to recent Rosat X-ray observations in the Cygnus Loop.

K. Shigemori (Osaka Univ.) and E. Liang (Rice Univ.) have been developing experiments to create a radiative blast wave in the laboratory, using the Falcon laser at LLNL. The experiments are carried out in collaboration with T. Ditmire and B. Remington at LLNL. The group has conducted an initial experimental study on blast-wave propagation in a gas cluster target to examine the properties of a radiative shock which is relevant to the supernova-remnant formation and interstellar medium dynamics. Experiments were performed in the FALCON laser facility at LLNL. Gas cluster targets (N2, Ar, Xe) are irradiated by Ti: sapphire laser (pulse duration: 30 fs, laser energy: 15 mJ). Since the absorption fraction of the gas cluster is very effective, a high temperature, low density plasma can be generated. The blast wave propagation was measured by the Michelson interferometry. The experimental results indicate that ionization is generated ahead of the shock wave due to radiative preheat. The radiative precursor was more significant for higher atomic-number gas. In collaboration, K. Keilty and E. Liang (Rice Univ.) are working on the modeling of the radiative blast wave by using the 1-D hydrodynamics code HYADES, plus astrophysics codes. The simulations also show the ionization ahead of the shock front similar to the experiment. The trajectories for the most radiative cases fall slightly below the classical Sedov-Taylor blast wave trajectory, indicating energy loss by radiation. In comparing to astrophysical shocks, the high Mach numbers ($M = 10 - 20$) are similar. However, the laboratory gas is at much higher density, so the radiation is coupled to the hydrodynamics, giving a radiative precursor. Typically in astrophysics, the densities are so low that the medium is optically thin, and radiation is simply a cooling mechanism, removing energy from behind the shock (but not redepositing energy ahead of the shock).

J. Stone and colleagues of the University of Maryland are developing high Mach number, radiative jet experiments using high intensity lasers. It is of great interest to the astrophysics community to benchmark radiative hydrodynamics codes against relevant astrophysical data. 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. The experiments are in collaboration with B.A. Remington and his team at LLNL. The group started this work on the Nova laser at LLNL to produce the first high Mach number, radiatively collapsing jet. This data will be utilized by J. Stone and his colleagues at the University of Maryland to test the radiation hydrodynamics code ZEUS. In these experiments, five of Nova's 10 beams directly illuminated the interior of a gold cone. The ablated gold radiatively collapsed to form a high Mach number ($M = 15$), narrow, hot jet. Based on numerical simulations, the radiative effects upon the hydrodynamics of the jet were very large. The jet temperature was initially very hot (electron temperature 1-2 keV), but cooled rapidly (within 1/2 nsec) through radiative losses which triggered the collapse of the jet on axis. Without radiation effects included in the simulations, the jet was a factor of 10 broader and hotter, and a factor of 10 less dense. The Nova-produced radiative jet was diagnosed with 2D time-resolved imaging of the jet's self-emission, as well as backlit images of the jet, giving density and velocity. Thompson scattering was used to determine the average temperature of the jet. A subsequent series of experiments were performed on the Gekko laser at Osaka University in Osaka, Japan. In the Gekko campaign, the $\langle Z \rangle$ of the jet was varied by using targets of Au, Fe, Al, and CH. The high $\langle Z \rangle$ jets (Au, Fe) radiatively collapsed on axis, but the low $\langle Z \rangle$ jets (Al, CH) did not. These data should prove invaluable for the benchmarking of radiative hydrodynamics, astrophysics codes and reinforce the utility of high energy lasers to the astrophysics community.

R. McCray (Univ. of Colorado) and R.P. Drake (Univ. of Michigan) carried out experiments on the Nova laser at LLNL to benchmark astrophysical codes used to model the radiative hydrodynamics of supernova remnant (SNR) evolution. Of particular interest is the supernova remnant now developing around SN1987A. The ejecta from this supernova is on a collision course with its circumstellar ring nebula, with impact expected imminently. The contact discontinuity between the forward and reverse shocks, where the ejecta meets the ambient medium, is thought to be Rayleigh-Taylor (RT) unstable, leading to large perturbations forming. The shock-induced Richtmyer-Meshkov instability may also contribute to the growth of these perturbations. Such RT-induced clumping could change the nature of the much awaited collision from a smooth, 1-D sweeping up of the ring, to something more akin to localized ''hydrodynamic bullets'' impacting the ring, in radiative bursts or ''sparkles.'' Indeed, the first indication of the collision in SNR1987A was a localized brightening of the ring observed last year. The astrophysics codes being used to predict the outcome of this extragalactic collision are being benchmarked with experiments on the Nova and Omega lasers, where times of 1 ns (from the laser experiment) scale to 1 year for the SNR, velocities of 100 km/s correspond to 10,000 km/s, and lengths of 100 micron scale to 0.03 light years. The experiments are in collaboration with B.A. Remington and his team at LLNL. Initial experiments were conducted in one dimension (1-D), to observe ejecta plasma flowing into a low density ambient plasma, forming a classic forward shock-reverse shock system, much like in the astrophysical SNR. These first experiments have described in several papers. The group has also conducted initial 2-D experiments to study the predicted shock-induced effects and Rayleigh-Taylor (RT) instability thought to occur at the contact discontinuity between the forward and reverse shocks. It appears that ''sparks are set to fly,'' both experimentally on the Omega laser and in the LMC galaxy were SNR1987A resid es.

2.8 Hydrodynamics Simulations of Star Formation Processes

R. Klein (LLNL, and UC Berkeley) with C. McKee and graduate student Kelly Truelove (UC Berkeley) have studied the collapse and fragmentation of molecular clouds in the galaxy using a high order accurate Three-Dimensional hydrodynamic code they have developed with Adaptive Mesh Refinement to achieve unprecedented resolution in their calculations. They demonstrated with a new 3-D adaptive mesh refinement code that perturbations arising from discretization of the equations of self-gravitational hydrodynamics can grow into fragments in multiple-grid simulations, a process they call artificial fragmentation. They investigated star-formation calculations of isothermal collapse of dense molecular cloud cores. In simulations of a Gaussian density profile cloud free of applied perturbations, they find that artificial fragmentation can be avoided across the isothermal density regime by ensuring the ratio of cell size to Jeans length, which they call the Jeans number J is kept below 0.25. They refer to the constraint that J be resolved as the Jeans condition. When an $m = 2$ perturbation is included, collapse to a filamentary singularity occurs without fragmentation of the filament, in agreement with the predictions of Inutsuka and Miyama (1992, 1997). Simulation beyond the time of this singularity requires an arresting agent to slow the runaway density growth. Physically, the breakdown of isothermality due to the buildup of opacity acts as this agent, but many published calculations have instead used artificial viscosity for this purpose. Because artificial viscosity is resolution-dependent, such calculations produce resolution-dependent results. In the context of the perturbed Gaussian cloud, they show that use of artificial viscosity to arrest collapse results in significant violation of the Jeans condition. They also show that if the applied perturbation is removed from such a calculation, numerical fluctuations grow to produce substantial fragments not unlike those found when the perturbation is included. These findings indicate that calculations that employ artificial viscosity to halt collapse are susceptible to contamination by artificial fragmentation. The Jeans condition has important implications for numerical studies of isothermal self-gravitational hydrodynamics problems insofar as it is a necessary but not, in general, sufficient condition for convergence.

R. Klein (LLNL, and UC Berkeley) with A. Boss (Carnegie Institution), R. Fisher (UC Berkeley) and C. McKee (UC Berkeley) have performed work on examining the Jeans Condition in collapsing molecular cloud cores to confirm the earlier work of Truelove *et al.* 1997, 1998 who showed that the Jeans condition is a necessary condition for avoiding artificial fragmentation during protostellar collapse calculations. They found that when the Jeans condition was properly satisfied, an isothermal cloud with an initial Gaussian density profile collapsed to form a thin filament. Using a different gravitational hydrodynamics code they reproduced the filamentary solutions found by Truelove, Klein, McKee, Howell and Greenough, Ap.J. 1997, 1998. They demonstrated that these collapse solutions appear to be a strong test on the reliability of gravitational hydrodynamic codes, whether grid based or particle based. They also showed that in the more physically realistic case of a cloud that undergoes non-isothermal heating, thermal retardation of the collapse permits the Gaussian cloud to fragment into a binary protostar system. They also confirmed that even in the case of isothermal collapse, an initially uniform density sphere can collapse and fragment into a binary system in agreement with the results of Truelove, Klein, McKee, Howell and Greenough Ap.J. 1998.

R. Klein (LLNL, and UC Berkeley) has written a review paper with P. Bodenheimer (UC Santa Cruz), A. Burkert (MPIfA, Heidelberg) and A. Boss (Carnegie Institution) 'The Formation of Multiple Stars'. This paper will appear in Protostars and Planets IV, Arizona Press, 2000. He has also written a review paper 'Star Formation with 3-D Adaptive Mesh Refinement: The Collapse and Fragmentation of Molecular Clouds' which will appear in The Journal of Computational and Applied Mathematics, (Elsevier Press), 2000.

R. Klein (LLNL, and UC Berkeley), T. Woods (UC Berkeley, SSL) and C. McKee (UC Berkeley) have investigated the 3-D collision of initially gravitationally stable interstellar clouds with extremely high resolution adaptive mesh refinement hydrodynamics. They have explored a wide range of cloud collisions with varying Mach number and impact parameter. They have mapped out the regime for initially stable clouds to become gravitationally unstable during cloud collisions. They have shown that various hydrodynamic instabilities during the collision phase can disrupt the coalesced system. They have demonstrated that triggered star formation by cloud collisions is difficult and may occupy a small phase space for head on or near head on collisions only over a certain range in Mach number.

A.B.E. Smith (Las Positas College) and S. Murray have written two spreadsheet-based astronomy labs for use in courses aimed at non-science majors. In one, students are introduced to Kepler's Laws, while in the other they are introduced to principles of stellar structure and the methods of computing numerical models of stars. Both spreadsheet programs include introductory material as well as procedures, allowing them to be used also in distance education environments. Movement through the labs, and saving final results is automated using Excel's VBA language. The labs are currently in use at Las Positas College, and are being made freely available to any interested instructors.

2.9 Stellar High Energy Astrophysics

M. Foord, J. Emig, R. Heeter, P. Springer and R. Thoe (LLNL) in collaboration with C. Deeney, J. Bailey, C. Coverdale and the Z-Machine team (Sandia Nat'l Labs), have completed preliminary experiments using 10 ns, 120 TW, 170 eV X-ray pulses from a Z pinch to produce photo-ionized iron plasmas in regimes similar to those found in accretion disks around compact objects. Follow-up experiments are planned for FY2000. The results will help benchmark several astrophysical models used to interpret data from Chandra, XMM, Astro-E and other X-ray observatories.

R. Klein (LLNL, and UC Berkeley), G. Jernigan (UC Berkeley) and J. Arons (UC Berkeley) reported the discovery of kHz fluctuations, including quasi-periodic oscillations (QPO) at 330 Hz and 760 Hz and a broadband continuum in the power density spectrum of the high mass X-ray binary pulsar Centaurus X-3. These observations were carried out with the Rossi X-ray Timing Explorer (RXTE). The fluctuation spectrum is flat from mHz to a few Hz, then steepens to f^{-2} behavior between a few Hz and 100 Hz. Above a hundred Hz, the spectrum shows QPO features, plus a flat continuum extending to 1200 Hz and then falling out to 1800 Hz. These results, which required the co-adding of three days of observations of Cen X-3, are at least as fast as the fastest known variations in X-ray emission from an accreting compact object and probably faster since extension to 1800 Hz is indicated by the most likely parameterization of the data. Multi-Dimensional radiation hydrodynamic calculations of optically thick plasma flow onto the magnetic poles of an super- Eddington accreting neutron star show that the fluctuations at frequencies above 100 Hz are consistent with photon bubble turbulence and oscillations (PBO) previously predicted (Klein *et al.* 1996, Ap.J. letters) to be observable in this source. They showed that previous observations of Cen X-3 constrain the models to depend on only one parameter, the size of the polar cap. For a polar cap opening angle pf 0.25 radians (polar cap radius 2.5 km and area 20 km^2, for a neutron star radius of 10 km), they showed that the spectral form above 100 Hz is reproduced by the simulations, including the frequencies of the QPO and the relative power in the QPO and the kHz continuum. This has resulted in the first moel-dependent measurment of the polar cap size of an X-ray pulsar. The discovery of Photon Bubbles Oscillations in a high mass X-ray pulsar opens the door to future X-ray observations with high resolution timing that will allow us to probe the physics of the surface of super-Eddington accreting X-ray pulsars.

C. Mauche used high-resolution far-UV (910-1210 Angstrom) spectra obtained with the ORFEUS II satellite to determine the physical characteristics and accretion geometries of two magnetic cataclysmic binaries: AM Herculis, a polar in which a spin- synchronous white dwarf accretes directly from its companion, and EX Hydrae, an intermediate polar in which accretion onto a spin-asynchronous white dwarf is moderated by a disk. Despite the significant differences in the overall geometry of these two systems, their mean far-UV spectra are very similar, with emission lines of C III, N III, O VI, and He II (in AM Her but not EX Hya) superposed on a nearly flat continuum. In both systems the continuum flux variations can be modeled as the varying visibility of a 40 kK spot in the vicinity of the upper magnetic pole of a 20 kK white dwarf. In both systems the O VI doublet is a superposition of broad and narrow components, but their radial velocity variations imply very different sources and geometries. In both systems the O VI broad component arises in the accretion funnel, but in AM Her, the FUV continuum peaks when the upper magnetic pole of the white dwarf points toward the observer - when the redshift of the O VI broad component is highest, whereas in EX Hya, the FUV continuum peaks when the magnetic pole points away the observer - when the blueshift of the O VI broad component is highest. The O VI narrow component arises in the irradiated face of the secondary in AM Her, and in the white dwarf in EX Hya. Various lines of evidence indicate that the density of the O VI broad and narrow emission line regions is between $3 \times 10^{10} cm^{-3}$ to $10^{12} cm^{-3}$.

C. Mauche wrote a review article concerning the EUV (70-180 Angstrom) spectra of polars (spin-synchronized magnetic cataclysmic binaries). The EUV emission of such systems arises from the accretion region in the vicinity of the magnetic pole(s) of the white dwarf. Of the 15 polars with data in the Extreme Ultraviolet Explorer (EUVE) archive, nine were found to have useful spectra. These data were extracted from the archive, reduced, and fit with three different models - a blackbody, a pure hydrogen stellar atmosphere, and a solar abundance stellar atmosphere - to reveal the presence of spectral features such as absorption lines and edges, and to investigate the sensitivity of the derived (kT, N_4H, solid angle) and inferred (fractional emitting area, bolometric luminosity) parameters to the model assumptions. Of these models, a blackbody provides the best phenomenological description of the EUVE spectra, but it fails to account for (1) the weak absorption edges of Ne VI and the absorption lines of Ne VII and Ne VIII apparent in the residuals of the sources with the highest signal-to-noise ratio spectra and (2) the likely inability of these moderately soft blackbodies to produce the observed soft X-ray fluxes. The untested irradiated solar abundance stellar atmosphere model is likely a better overall description of the EUV/soft X-ray spectra of polars,, but better models (which include, e.g., absorption lines as well as edges) and better data (e.g., high signal-to-noise ratio phase-resolved Chandra LETG spectra) are required to make additional progress in our understanding of the accretion region of polars.

P. Vitello has continued his research on line-radiation winds from cataclysmic variable accretion disks in collaboration with I. Shlosman (U. Kentucky) and A. Feldmeier (U. Kentucky). Work continued on an analytic model of two-dimensional stationary, line-driven winds from accretion disks in cataclysmic variable stars. Model predicts for the mass loss rates and velocity laws are in agreement with observational data.

2.10 Kuiper Belt Objects

C. Alcock, K. Cook, M. Hammergren, and S. Marshall are collaborating with I. de Pater, C. Liang, and J. Rice (UC Berkeley); J. Lissauer (NASA/Ames); T. Axelrod (MSSSO, Australia); T. Lee and C.-Y. Wen (Academia Sinica, Taiwan); and Y.-I. Byun, W.-P. Chen, and W.-S. Tsay (National Central U., Taiwan) 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 three small telescopes to be located in the Yu Shan National Park in Taiwan. The telescope system is nearing completion and will be delivered to LLNL during the first months of 2000. Integration of the telescopes, CCD cameras, enclosures and automated detection systems will take place in Taiwan during the first six months of 2000 with initiation of automated operation expected during the second half of 2000.

2.11 Asteroids

K. Cook (LLNL), C. Stubbs and A. Diercks (U/Wash.), and T. Bowell and B. Koehn (Lowell Obs., Arizona) have completed an innovative 2048 by 4096 pixel scanning CCD camera, which operates at prime focus on an 18-in. Schmidt telescope on Anderson Mesa in Arizona. This system is the heart of the Lowell Observatory Near-Earth Object Survey (LONEOS), and allows about 1000 square degrees per night to be triple-scanned to detect near-Earth objects through their rapid apparent motion. The LONEOS system began taking data with the newly refurbished Schmidt telescope in 1997. It was decided, however, that the corrector and field flattener that were being used needed to be refabricated. These elements was reinstalled during the winter of 1998, and the system has been operational since that time. It discovered its first NEO 1998 MQ in June, 1998. The survey has discovered a total of 17 new Near Earth Objects and 6 new comets.

M. Hammergren (LLNL) reported the results of an extensive spectroscopic survey of near-Earth objects, in a talk given at the 1999 Asteroids Comets Meteors Conference in Cornell, NY. After removing observational biases and selection effects, it is seen that the near-Earth object population is dominated in both apparent and real numbers by the relatively bright, silicate-rich S-type asteroids, with a substantial minority being the darker, carbon-rich C-types. This distribution of types is very similar to that seen for asteroids in the inner main belt, which on theoretical grounds has long been considered the primary source region for near-Earth o bjects.

M. Hammergren (LLNL) has examined the shapes and rotation rates of more than 850 asteroids, and concluded that the more elongated objects have a lower maximum limit on spin rates than the more spherical ones. In a presentation at the 1999 American Astronomical Society conference in Chicago, IL, Hammergren showed that such a shape-dependent limit is consistent with most asteroids being ''rubble piles,'' or essentially strengthless objects bound together by their self-gravity. Hammergren is also investigating the structural properties of ''rubble pile'' asteroids under the explicit assumption that they are composed of granular, and not fluid, material. Some preliminary models show that the rotational deformation of such objects proceeds catastrophically via landslides or avalanches, and results in shapes which are significantly different from ellipsoidal figures of equilibrium. Furthermore, there exists a maximum rotation rate for elongated objects, beyond which rotational deformation must result in mass shedding. This behavior may help explain the phenomenon of comet nucleus splitting, and the existence of asteroid satellites.

M. Hammergren (LLNL) continued his studies of solar system objects as an external collaborator in the Solar System working group of the Sloan Digital Sky Survey (SDSS). Hammergren has produced a theoretical asteroid taxonomy based on synthetic five-color SDSS photometry, and has shown that early results from SDSS commissioning data demonstrate the potential for producing good taxonomic information on tens of thousands of asteroids which will be observed during the course of the survey.

2.12 Adaptive Optics

C. Max, S. Olivier, J. Brase, D. Gavel, B. Macintosh, H. Friedman and other colleagues at LLNL together with collaborators from three UC campuses, are developing laser guide stars for astronomical adaptive optics. The goal of this project is to improve the angular resolution achieved at ground-based observatories. If the project is successful, the angular resolution at major observatories might be improved by 10-100%.

The angular resolution of ground-based telescopes with apertures larger than 10-20 cm is limited to about a second of arc because of turbulence in the atmosphere. In principle, by deforming a flexible tertiary mirror to make the wavefront nearly flat, adaptive optics can be used to correct for the wavefront distortions, which are measured with a wavefront sensor. This correction would allow ground-based telescopes to be operated at or near their diffraction-limited bounds. For example, at a wavelength of 1 μ, the diffraction-limited resolution would be 0.08 arcsec for a 3-m telescope and 0.02 arcsec for a 10-m telescope. These represent improvements in resolution of factors of 25 and 100, respectively, relative to the atmospheric resolution of about 1 arcsec. To produce this correction, one needs a bright reference object within a few arcseconds of the object being imaged. The statistics of bright stars are such that only a few percent of the sky is accessible for diffraction-limited viewing using nearby bright stars as the wavefront reference.

To make up for the lack of bright reference stars, this consortium is developing the ability to produce artificial stars using a powerful laser. The idea is to use a laser tuned to the sodium D lines to resonantly excite the atmosphere sodium layer at 90-km altitude, which makes an artificial star to serve as a reference beacon. A wavefront sensor detects the tilts of the reference wavefront, and a wavefront computer uses the reference wavefront to calculate the adaptive-optics corrections. Finally, the correction is applied to a deformable mirror. The images recorded using the deformable mirror, with the telescope's primary mirror, will have most of the atmospheric distortions removed. A 20-W dye laser and an adaptive optics system (both developed at LLNL) have been installed on the Lick Observatory 3-m Shane telescope. The laser is based on technology developed for the LLNL Atomic Vapor Laser Isotope Separation (AVLIS) program and produces an eighth-magnitude artificial guide star, sufficient for adaptive optics correction of the 3-m telescope at wavelengths of 1-2 μ. The system has been used to develop the calibration and observation techniques that all other laser guide star AO systems will need as they become operational on large telescopes.

The system also demonstrates excellent performance using bright natural guide stars as references. Natural-guide-star science programs studying young stellar objects, binary stars, and the outer planets are being carried out in collaboration with Prof. A. Ghez (UC Los Angeles), Prof. I. de Pater (UC Berkeley), and Prof. J. Graham (UC Berkeley). M. Liu and J. Patience, students of Profs. Graham and Ghez respectively, have carried out a systematic search for stellar companions to the stars known to have planets orbiting them-an attempt to see if perturbations by previously unknown stellar companions can explain the bizarre planetary systems recently discovered by Prof. G. Marcy (UC Berkeley) and collaborators. Observations of the outer gas giant planets Neptune and Uranus are being fit to radiative transfer models developed by Prof. de Pater and her graduate student H. Roe. Science programs using the laser guide star to study fainter targets will also be carried out.

The LLNL group also worked on the real-time control and low-level software for the adaptive optics system for the 10-m W.M. Keck Telescope. The LLNL contribution was integrated with an optical bench built by the Keck Observatory AO team, and achieved first light in February 1999. The Keck AO system is now routinely producing near-diffraction-limited images with resolution better than 0.05 arcseconds on a variety of targets. LLNL astrophysicsts, led by Max and Macintosh, participated in early science tests of the system, including studies of young stellar objects and stunning images of Neptune.

2.13 Speckle Imaging of Titan, Io, and Neptune

C. Max, D. Gavel, B. Macintosh, and S. Gibbard (LLNL), working with collaborators from UC Berkeley, NASA Ames, the Southwest Research Institute, and JPL, continued to observe solar system objects at very high spatial resolution using the technique of speckle imaging. Speckle imaging uses a series of very short exposures to ‘‘freeze’’ the turbulence of the Earth’s atmosphere, which limits the resolution of most ground-based observations to 0.5 arcseconds. Near-infrared observations were obtained at the 10-meter W. M. Keck Telescope of Saturn’s moon Titan, Jupiter’s volcanically-active moon Io, and Neptune. The speckle imaging technique allowed to obtain spatial resolution near the diffraction-limit of the telescope, 0.04 arcseconds at a wavelength of 2 microns.

Titan, Saturn’s largest moon, is unique among planetary satellites in possessing a thick atmosphere. Seen in visible light, Titan is shrouded in a featureless, orange haze. This haze is believed to be composed of organic compounds produced by the photolysis of methane. Models suggest that this haze gradually settles to Titan’s surface, and over long periods of time, could form oceans, lakes, or underground reservoirs of liquid. Excellent images of Titan’s leading (brighter) hemisphere and the darker trailing hemisphere were obtained. The data were taken through the K’ and H filters, which include both a strong methane absorption band, which provides data on Titan’s atmospheric structure, and a window in the band through which we can see surface features on Titan. This technique allows one to obtain interesting information both about the surface and about previously unknown characteristics of Titan’s atmosphere.

These data clearly show a continent-sized bright surface feature on Titan’s leading hemisphere, which is consistent with icy or rocky highlands, as well as a very low albedo region that is consistent with the presence of liquid hydrocarbons on the surface. Titan’s darker hemisphere has a very low albedo ($< <0.05$) overall, with some brighter areas. If Titan’s dark areas are liquid hydrocarbons, this would be the first detection of surface liquids on a solar system body other than the Earth.

Io, the innermost large moon of Jupiter, experiences tidal stresses and enough internal heating to create volcanoes on its surface. By observing Io in the infrared while the Sun is eclipsed by Jupiter, emission from individual volcanoes can be imaged or even resolved. These data may be used to determine the time variations, size, spacing, and number of volcanoes, which in turn yields information about the nature of these volcanoes, particularly the high-temperature events thought to be silicate volcanism. Seventeen individual volcanic features on Io’s surface were resolved in observations during an eclipse in July 1998. The Keck observations of Io represent the highest resolution infrared measurements available to date.

Neptune is a very dynamically active planet of which little is known because of its small angular extent (2.5 arcseconds). Voyager 2 detected prominent dark and bright spots at visible wavelengths, as well as some bright wispy cloud features. These features change on timescales varying from hours to years. The goals in observing Neptune are to determine the altitude and composition of the material that makes up the infrared-bright features on the disk of Neptune; to determine the timescales over which these features evolve; to look for oscillations in spot size or shape; and, ultimately, to determine the contribution of these storms to Neptune’s overall heat budget.

Neptune was observed in speckle mode at H band, and in conventional mode using infrared narrow bands. The latter probe different heights in Neptune’s stratosphere. Using a model adapted from a Neptune radiative transfer code developed by K. Baines (JPL), it was possible to constrain the number density of Neptune’s stratospheric haze layers and to verify that the infrared-bright storm features are, indeed, located in Neptune’s stratosphere rather than lower down in the troposphere.

2.14 Instrumentation

Resolving a long-standing puzzle, J. Drake (Center f. Astrophysics) together with G. Brown, P. Beiersdorfer , and S. Kahn (Columbia U) used Livermore EBIT data to make a definitive identification of a feature at 17.62 Angstrom in solar spectra. They showed that the feature arises from a transition in Fe XVIII. This transition was not predicted by earlier atomic calculations. Photospheric fluorescence of Fe L-alpha was shown to be too weak to account for the observed emission.

In preparation for the spectral observations carried out with the Chandra X-ray Observatory, G. Brown, P. Beiersdorfer and S. Kahn (Columbia U) have carried out spectral surveys of the iron L-shell emission in the 10 – 17 Angstrom wavelength band using the Livermore Electron Beam Ion Trap laboratory astrophysics facility. The measurements produced accurate line positions and relative intensities and covered all ionization stages between Fe XVII and Fe XXIV. K. Phillips (Rutherford Labs) and collaborators used these data to make a comparison with solar data from the SMM mission. The higher wavelength accuracy doubled the quality of global spectral fits to the solar data.

S. Labov, M. Frank, A. Loshak, M. van den Berg, S. Friedrich (LBNL, and LLNL), D. Chow, M. Cunningham, O. Drury, L.J. Hiller, M. A. Lindeman (UC Davis, and LLNL), and A.T. Barfknecht (Conductus, Inc.) 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. 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.

W. van Breugel (LLNL) and J. Bland-Hawthorn (AAO, Australia) organized a major international conference on 'Imaging the Universe in Three Dimensions: Astrophysics with Advanced Multi-Wavelength Imaging Devices', under the auspices of LLNL, in Walnut Creek, California, from March 29 - April 1, 1999. The purpose of the meeting was to bring together instrumentation experts and observers to discuss the new opportunities afforded by the new class of advanced multi-wavelength imaging intruments that are currently being designed for major ground- and space-based observatories. There are many examples of '3-Dimensional' instruments, which include quasi-simultaneous spatial and spectral coverage over large fields and wavelength ranges (e.g., 2 spatial, 1 spectral). These include multi-beam imaging cameras and spectrographs, integral field spectrographs, tunable (e.g., Lyot, acousto-optic, liquid crystal) filters, Fabry-Perots, and Fourier transform spectrographs. New 'enabling' technologies that are already extending the capabilities of these instruments include adaptive optics, micromirrors, staircases (image slicers), 3-D photon detectors, superconducting tunnel junction devices, sky suppression techniques, tunable gratings, and so on. The meeting was attended by 130 participants, many from foreign countries, representing all of the major observatories and institutions with significant 3-D intrumentation programs. W. van Breugel and J. Bland-Hawthorn co-edited the proceedings for this meeting, which will be published in the Astronomical Society of the Pacific Conference Series. 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 is will serve as an important reference work on advanced multi-wavelength imaging.

E. Wishnow is the Project Scientist for 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. The instrument will be commissioned on the Keck I telescope in the fall of 1999. LWIRC is a joint project of the Space Sciences Laboratory of UC and LLNL. R. Wurtz and K. Cook are also LLNL collaborators in this project.

E. Wishnow (LLNL), H. Gush, I. Ozier (University of British Columbia) and J. Schaefer (Max Planck, Garching) have studied the collision-induced spectrum of low temperature hydrogen gas. This work involved precise measurements of the hydrogen spectrum from 20 to 320 wavenumbers (500–31.3 microns), over the temperature range 22–38 K, using a unique cryogenic long pathlength absorption cell. At these low temperatures, quantum mechanical aspects of the hydrogen molecule are significant and theoretical spectra calculated from first principles have been compared to the measurements; the correspondence is the most exact obtained in the the field of collision-induced spectroscopy. This work is relevant to interpreting the far-infrared spectra of planetary atmospheres and spectra of cold molecular clouds.

The V Division Astrophysics Group has been developing advanced instrumentation for ground and spaced-based astronomy and continues these efforts with the development of imaging Fourier transform spectrometers for astronomy. C. Bennett, K. Cook, E. Wishnow and R. Wurtz are building and fielding an imaging Fourier transform spectrometer for operation in the visible and the mid-infrared. This system is a 4-port Michelson interferometer. The prototype, operating in the wavelength range from 0.4 to 1 micron, provides a high throughput, flexible resolution instrument for projects ranging from low resolution 'broad-band' photometry studies to medium resolution kinematic studies. Results from test observations at the McMath-Pierce Solar telescope in March were presented at the June American Astronomical Society meeting. This project supports the development of an imaging Fourier transform spectrometer for the Next Generation Space Telescope (NGST) through a pre-Phase A proposal to NASA. The Integral Field Infrared Imaging Spectrometer (IFIRS) proposal was selected for further study by NASA as a science instrument for NGST. NGST is a space-borne 8 meter telescope which is being designed specifically to conduct observations of the high-redshift, very early universe. The IFIRS team is led by J. Graham of UC Berkeley and consists of members from LLNL, ITT, NRL, and NOAO. IFIRS is a wide field instrument operating in the near and mid-infrared yielding spectra of flexible resolution for all pixels in the focal plane and is capable of performing the straw-man Design Reference Mission proposed for NGST by itself and in less time than the proposed ’Yardstick’ instrument complement at a considerable cost savings.

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