Lawrence Livermore National Laboratory

Livermore, California 94550

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1. INTRODUCTION

The Lawrence Livermore National Laboratory (LLNL) is operated by the University of California (UC) under U.S. Department of Energy Contract No. W-7405-ENG-48. The primary missions of the Laboratory involve national defense and energy problems; in addition, basic research in a number of areas is supported full time. Research in astrophysics is carried out in three closely affiliated groups: the Institute of Geophysics and Planetary Physics, P-Division, and V-Division within the Physics and Space Technology Directorate and on a part-time basis by about 20 other scientists, who have additional responsibilities in the large LLNL programs.

Since 1983, the LLNL branch of the University of California's Institute of Geophysics and Planetary Physics (IGPP) has acted as the focus of most astrophysics activities at LLNL. C. Alcock is the Director of the LLNL branch of IGPP, which is organized into two centers led by C. Alcock (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 $459,000 to UC campus faculty and staff members, enabling 21 collaborative projects. The senior staff at the Astrophysics Center at IGPP consists of C. Max, C. Alcock, K. Cook, and W. van Breugel. In addition, there are several full-time postdoctoral fellows and researchers: D. Bennett (now at Notre Dame), M. Brotherton, P. Fiske (now a White House Fellow), S. Laurent-Muehleisen, S. Gibbard, M. Gregg, K. Jedamzik (now at ESO), B. Macintosh, S. Marshall, D. Minniti, E. Moran, S. Rhie (now at Notre Dame), A. Stanford, and a large number of faculty and student visitors from the UC campuses. Among these, R. Becker (UC Davis) spends a considerable portion of his time in the IGPP.

The Physics and Space Technology 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 in V-Division works to channel LLNL expertise in ultraviolet, X-ray, and gamma-ray instrumentation, as well as large-scale computing, into astrophysics applications. The Astrophysics Group is a collaborative venture with UC campus scientists, and is presently developing astronomical instruments for X-ray spectroscopy, gamma-ray spectroscopy and imaging, X-ray polarimetry, and multi-object optical spectroscopy. The Astrophysics Group is also involved in a variety of astrophysical investigations including astronomical observations, theoretical modeling, and laboratory measurements. LLNL physicists J. Bixler, K. Cook, D. Dearborn, W. Goldstein, S. Labov, D. Liedahl, C. Mauche, C. Mears, H. Park, 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.

Astrophysics research is a prominent component of P-Division in the Physics and Space Technology Directorate . Current astrophysics staff in P-Division include T. Weaver and R. Eastman. In addition, P-Division benefits from a number of academic consultants (R. Chevalier, Virginia; P. Moller, LANL; R. Boyd, Ohio State; J. Cowan, Oklahoma; C. Evans, Caltech; G. Mathews, Notre Dame), and participating guests (K. Hurley, UC Berkeley; E. Eveno, Toulouse, France; R. Emmering, Caltech) who collaborate with P-Division staff on joint projects.

2. RESEARCH

2.1 Cosmology

Extending earlier work, M.D. Gregg has derived the diameter - velocity dispersion relation in B, V, and K for three early type galaxies in the Leo I (M96) group from published photometric and kinematic data. The relations in all three colors have slopes which agree well with those for the Coma cluster. The RMS scatter of the Leo I galaxies in each color is extremely small, consistent with the group's compactness. These relations yield estimates of the Coma–Leo I distance ratio of 9.01 ± 0.51, 8.77 ± 0.43, and 8.82 ± 0.31 respectively, with a weighted mean of 8.84 ± 0.23. The Coma–Leo I distance ratio coupled with estimates of the distance to the Leo I group allows the Hubble constant to be determined. Several high quality distance estimates are available from a variety of techniques: Cepheids in M96 and M95 (Graham *et al.* 1997), surface brightness fluctuations, planetary nebulae luminosity functions, and the luminosity of the red giant branch tip. These distance estimates lead to values of the Hubble constant ranging from 71 to 85 $kms^{-1}mpc^{-1}$, with the extremes differing by 3 standard deviations. A value near the low end of the range is preferred.

K. Jedamzik has considered the formation of primordial black holes from pre-existing density fluctuations during early cosmic phase transitions. He has have shown that the effective speed of sound during first-order cosmic phase transitions does vanish. This fact implies that there may be abundant black hole formation on the horizon mass scale during the phase transition epoch. In the case of a first-order QCD transition he has shown that for generic inital conditions this may lead to a peaked black hole mass function at $M_{BH}\sim 1M_{\odot}$. He has pointed out that this mass scale is roughly coincident with the estimated masses for compact objects recently observed in our galactic halo by the MACHO collaboration. Black holes formed during the QCD epoch may offer an attractive explanation for the origin of halo dark matter evading possibly problematic nucleosynthesis and luminosity bounds on baryonic halo dark matter.

K. Jedamzik, in collaboration with J. Prochaska (UCSD), have used recent spectral high-resolution data of damped Lyman α systems at high redshift in order to constrain the properties of proto-galactic disks in a variety of popular structure formation scenarios. Damped Lyman α systems at high redshift are commonly believed to be associated with the progenitors of present-day galaxies. High resolution data yields important information about the intrinsic velocity distribution of the cold gas constituting a damped Lyman α system. This information may be used to infer the masses of the protogalactic halos hosting the damped Lyman α system and the properties of the disk. They have compared the observationally determined frequency of damped Lyman-alpha systems to theoretically predicted ones for a variety of structure formation scenarios and protogalactic disk models. In general, They have found that for most structure formation scenarios protogalactic disks have to be larger and thicker than their present day counterparts. Conversely, some structure formation scenarios can not account for the observed abundance of damped Lyman-alpha systems at high redshift, given any disk model, and may therefore regarded to be not compatible with observations.

K. Jedamzik and G. M. Fuller (UCSD) have continued their study on deuterium observed in Lyman-limit systems at high redshift. Detections of deuterium in high redshift Lyman limit absorption systems along the line of sight to QSOs promise to reveal the primordial deuterium abundance. At present, the deuterium abundances (D/H) derived from the very few systems observed are significantly discordant. Assuming the validity of all the data, if this discordance does not reflect intrinsic primordial inhomogeneity, then it must arise from processes operating after the primordial nucleosynthesis epoch. They have considered processes which might lead to significant deuterium production/destruction, y*et al.*low the cloud to mimick a chemically unevolved system. These processes include, for example, anomalous/ stochastic chemical evolution and D/^{4}He photo-destruction. In general, they have found it unlikely that these processes could have altered significantly (D/H) in Lyman limit clouds. They have argued that chemical evolution scenarios, unless very finely tuned, cannot account for significant local deuterium depletion since they tend to overproduce ^{12}C, even when allowance is made for possible outflow. Similarly, D/ ^{4}He photo-destruction schemes engineered to locally produce or destroy deuterium founder on the necessity of requiring an improbably large γ-ray source density. Future observations of (D/H) in Lyman limit systems may provide important insight into the initial conditions for the primordial nucleosynthesis process, early chemical evolution, and the galaxy formation process.

K. Jedamzik, in collaboration with V. Katalinic (U Chicago) and Angela O. (U Chicago) have continued their effort in understanding the damping of magnetic fields in the early universe. They have studied the evolution of magnetic fields in an expanding plasma composed of relativistic and non-relativistic particles. They have derived the dispersion relations for the propagating MHD modes—fast and slow magnetosonic, sonic, and Alfvén waves—in the presence of viscosity and heat conductivity. They have found that all four modes are damped on scales up to the particle diffusion length. They have applied their results to the propagation of MHD modes in the early universe by deriving the appropriate sources of viscosity due to the decoupling of neutrinos and photons. Neutrino diffusion damps all modes on mass scales inside the horizon at the time of neutrino decoupling, $M_{d\nu}\approx 10^{-3}M_{\odot}$, and helps ensure that magnetic fields generated prior to neutrino decoupling satisfy primordial nucleosynthesis constraints. As the universe recombines, MHD modes are damped by photon diffusion up to the Silk mass, $M_{d\gamma}\approx 10^{13}M_{\odot}$, providing a natural ultraviolet cutoff to the spectrum of primordial magnetic fields. The presence of this cutoff constrains models in which galactic magnetic fields are essentially primordial. It also constrains models for galaxy formation which use predominantly primordial magnetic fields to generate density perturbations.

K. Jedamzik with G. Sigl (U Chicago) and A. Olinto (U Chicago) have given an estimate of primordial magnetic field generation during cosmic first-order phase transitions, such as a first-order electroweak transition or QCD transition. They have shown that generally it is expected that electric charge separation occurs at the surfaces of bubbles of new phase. They have considered instabilities on the surfaces of such bubbles which, in turn, may lead to the generation of electric currents and magnetic fields. They have found that viscous damping of such instabilities can be important in the QCD case, but that it is unlikely to be important in the electroweak case. They have discussed the possible amplification of these magnetic seed fields by turbulent fluid flow during the transition and estimated the strength and spectrum of the resulting remnant magnetic field at the present epoch.

2.2 Dark Matter

C. Alcock, D. Bennett (now at Notre Dame), K. Cook, S. Marshall, and D. Minniti are collaborating with C. Stubbs, A. Becker, M. Pratt (U Washington); K. Griest, J. Guern, and M. Lehner (UC San Diego); W. Sutherland (Oxford); R. Allsman, T. Axelrod, K. Freeman, B. Peterson, P. Quinn (now at ESO), and A. Rodgers (Mt. Stromlo and Siding Spring Obs.) on a search for dark matter in the galactic halo. Specifically, they are searching for evidence that galactic dark matter is made up of brown dwarfs and related objects, now known collectively as MACHOs (MAssive Compact Halo Objects). The signature of these objects is the rare amplification of background stars by the gravitational lens effect. In order to search for this signature, the 1.3-m ''Great Melbourne Telescope'' at Mt. Stromlo has been rebuilt and brought into operation. Two cameras, each containing four 2048*2048 CCDs, are used at prime focus; a dichroic beam-splitter allows imaging simultaneously in a red and a blue-green pass-band. The CCDs are read out through a 16 channel system and the data are immediately passed into the computer system, where reductions are performed, and the images and reduced photometry are automatically archived. The system has been operating for three years, and more than 50,000 images of the Large and Small Magellanic Clouds, and the Galactic bulge, have been taken. Preliminary reductions of some of these data have yielded $\sim$120 microlensing events. The estimated event rate toward the Large Magellanic Cloud is higher than can be accounted for by any previously known population of objects. The estimated event rate toward the galactic bulge is significantly higher than upper limits that were previously calculated using standard models for the galaxy.

The LMC results are particularly interesting, since they establish that planetary mass and brown dwarf mass objects do not comprise a significant fraction of the dark halo, but that objects of mass $\sim 0.5 msun$ do comprise a significant fraction, of order ~ 0.5 of the total.

The Macho Project now routinely detects microlensing events early in their history. Information regarding these ''alerts'' is posted on the World Wide Web (http://darkstar.astro.washington.edu/) and may be followed up at observatories throughout the southern hemisphere (or at low northern latitudes for bulge events). The Macho Project observes events in follow-up mode from CTIO and has obtained additional data in follow-up mode with other southern telescopes.

The first detection of the ''proper motion'' effect has been seen in an event. This occurs when the impact parameter of the Macho is so small that the finite angular size of the star must be included in the light curve fit.

The first detection of the ''parallax'' effect has been seen in an event. This occurs when the duration of the event is long enough that the motion of the Earth around the Sun has a discernible effect on the lightcurve.

D. Alves, a graduate student from UC Davis, has undertaken the task of calibrating the Macho photometry database. The Macho instrumental blue and red magnitudes for 9 million stars presently being monitored in the LMC have been transformed to the Cousins V and R system.

S. Marshall is developing, (along with UCSD graduate student T. Vandehei), a new system to measure microlensing event detection efficiencies. The technique is based on a characterization of the response of the MACHO photometry system to changes in flux of individual stars in crowded fields. To achieve this, false stars are added at various magnifications to MACHO project images taken in a wide range of seeing and sky level conditions. The measured responses will be used to generate model microlensing light curves that serve as input to a Monte Carlo analysis of the MACHO project event detection algorithms.

In the past year, a large-scale experiment to search for dark-matter axions has been successfully commissioned and begun production data-taking. The principle of the experiment relies on the resonant conversion of axions into monochromatic microwave photons in a high-Q cavity permeated by a strong magnetic field. The very weak signal expected (on the order of 10^{-22} Watts) may be seen above the noise background by virtue of the long integration time at each frequency, on the order of a minute, as the cavity is slowly step-tuned. In addition to the medium-resolution channel which searches for structures with fractional width of 10^{-6}, a high-resolution FFT spectrum is recorded (10^{-11}) to search for the fine-structure predicted in the axion spectrum by Sikivie *et al.*, owing to incomplete virialization of the CDM infall. The decade of mass between 10^{-6} and 10^{-5} eV will be scanned in the next three years. LLNL principals include C. Hagmann, D. Kinion, W. Stoeffl, K. van Bibber; collaborating institutions include MIT, University of Florida, FNAL, LBNL and INR/Moscow.

2.3 Galaxies, Active Galactic Nuclei, and Quasars

During 1996, R. Becker (UC Davis) in collaboration with M. Gregg and S. Laurent-Muehleisen continued to work on the VLA FIRST Survey. During this year the sky coverage increased to $\sim$3000 square degrees. The number of catalogued radio sources increased to $\sim$250,000. Using Lick, Keck, and Kitt Peak Observatories, followup programs on quasars, clusters of galaxies, BL LACS, and variable sources are in progress.

S.A. Stanford joined IGPP as a postdoctoral researcher in November 1995. Stanford's main research focusses on high redshift galaxy clusters. In the last year in collaboration with P. Eisenhardt (JPL) and M. Dickinson (STScI), he has completed a groundbased optical to near-IR imaging survey of 40 clusters from z=0 to 0.9. For a subset of this sample (16 clusters), HST/WFPC2 images were obtained from the STScI Archive and examined to produce Hubble types for all cluster galaxies. The optical to near-IR colors of the resulting samples of E/S0 galaxies were then compared with galaxy evolution models and with the colors of present epoch early-type galaxies to search for evolutionary trends with redshift. Stanford found a clear and nearly monotonic change towards bluer colors in the cluster E/S0s with increasing redshift. This result is in agreement with standard passive evolution. Furthermore, he found that the intrinsic scatter in the colors was small and nearly constant with redshift, indicating that the early-type galaxies form an old, coeval population which must have formed at a redshift $z > 3$. A paper reporting these results was presented at the 37th Herstmonceux conference in England.

In collaboration with van Breugel and D. Stern (UC-Berkeley), Stanford began a project to find high redshift ultraluminous IR galaxies. A sample was constructed from a positional correlation of the IRAS Faint Source Catalog and the FIRST catalog. Of the resulting 2000 matches, a subsample was drawn of objects which had either faint or no optical counterpart on the Palomar Sky Survey and which followed the well-known radio-FIR flux correlation. Stanford and Stern then observed the first group of such objects at the Lick 3m and found that 95% of them are ultraluminous IR galaxies at redshifts z=0.2 to 0.9, placing them among the most distant galaxies of their class. Also, many of the objects show signs of morphological peculiarities, suggesting that galaxy interactions and/or mergers could be the cause of their enormous far-infrared luminosities.

In the last year, a deep wide-field near-IR field galaxy imaging survey of which Stanford is a part was completed. This survey covers 100 square arcmin, reaches a K band limiting mag of 21.5, and includes the J,I,R, and B band imaging as well as the K band. In collaboration with R. Elston (NOAO) and P. Eisenhardt (JPL), Stanford discovered a spatially-concentrated group of very red galaxies while analyzing the dataset. These galaxies appear to have the properties of a rich galaxy cluster at z=1.3. A proposal was made to and accepted by STScI to obtain HST/WFPC2 images of the candidate cluster in Cycle 6 to examine their morphologies. To confirm the redshift and cluster identification Stanford is collaborating with H. Spinrad (UC-Berkeley) to obtain deep spectroscopy at the Keck Telescope.

The FIRST Bright Quasar Survey collaboration (R. Becker (U.C. Davis), M.D. Gregg (IGPP/LLNL), D. Helfand (Columbia), R. White (STScI), I. Hook (ESO), and R. McMahon (Cambridge) published its initial results and continued to pursue optical spectroscopy of QSO candidates. The number of identified candidates is now > 150. One of the quasars (0840+3633) found this year is a low-ionization, broad absorption line (BAL) QSO which also has absorption from metastable, excited states of iron. A similar object (1556+3517) was found in another FIRST-based search for high redshift QSOs being carried out by Hook *et al.* (1996). Out of the 8600 known quasars, there is only one other example of this type of QSO, 0059-2735. The FIRST Survey is picking up this rare subclass with much greater frequency than previous QSO searches, possibly an indication that these objects are not rare at all. They are heavily obscured and do not have the prominent emission lines of typical QSOs, perhaps explaining why they are missed in optical surveys. The object 1556+3517 is the first known radio-loud BAL QSO while 0840+3633 is ''radio-moderate;'' these objects may be transition objects between radio-loud and radio-quiet QSOs.

W. van Breugel, A. Cimatti (Arcetri Observatory) and A. Dey (NOAO), in collaboration with Antonucci (UCSB) continued his investigations of the origin of the extended (up to 60 kpc), radio-aligned, restframe UV continua in high redshift radio galaxies using the Keck spectropolarimeter. Nearly a dozen radio galaxies have now been observed, and virtually all of these show highly polarized rest-frame UV continua, with the electric vector perpendicular to the radio/UV axis. Broad and polarized MgII2800 line emission was also found in several objects. These observations show that most of the radio-aligned UV continuum in high redshift radio galaxies is due to anisotropic nuclear radiation scattered by dust/electrons toward the observer, in agreement with earlier suggestions based on low signal-to-noise data. They are in strong support of 'Unified' models in which radio galaxies are obscured quasars in the sky-plane. A surprising exception to these general conclusions has been found in the case of the 'proto-type' aligned radio galaxy 3C368. This object showed no polarized emission in deep Keck spectra, unlike previously reported observations with 4m-class telescopes. In this case the UV continuum is most likely due to nebular continuum associated with bright emission-line regions along the radio source axis.

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

W. van Breugel, in collaboration with M. Lehnert (Leiden Observatory), T. Heckman (JHU) and G. Miley (Leiden Observatory) continued his studies of the host galaxies of high redshift, radio-loud quasars. Ground-based data and more recently obtained high-quality HST imaging data have revealed many fascinating properties of the host galaxies of high redshift quasars. Quasar fuzz shows strong nebular emission, super-galactic size scales (tens of kpc) of the line and continuum emission, continuum spectral energy distribution similar to those of present-day Magellanic Irregulars or very late type spiral galaxies (but on average, redder than the nuclei of the associated AGN), K magnitudes that fall along the band defined by the radio galaxies in the IR Hubble diagram (K magnitude versus redshift), and rest-frame optical/UV luminosities about ten times more luminous than the most luminous galaxies in the present-day universe. Moreover, the ground-based data revealed very asymmetric emission line and continuum morphologies for the fuzz, and a weak tendency for quasars to exhibit an ''alignment effect'' like radio galaxies. Recent HST images now suggest that these asymmetric morphologies are due to interactions with nearby companions or to galaxies responsible for intervening absorption systems. They imply that quasars only exhibit a weak radio-UV/optical alignment: the aligned component, while seen, makes only a minor contribution to the total luminosity of the fuzz.

W. van Breugel, in collaboration with H. Röttgering, M. Lehnert (Leiden Observatory), and A. Dey (NOAO) continued his search for molecular gas (CO) from high redshift IRAS quasars and radio galaxies using the JCMT 15m and IRAM 30m telescopes. Despite deep integrations no detections were made of a sample of half a dozen of these objects. This confirms similar negative results from other groups. The only detections of high redshift IRAS objects have been of galaxies/quasars which have been amplified by an order of magnitude due to foreground gravitional lenses. It is likely that sensitivities much better than 1mK RMS must be achieved, using interferometers, to detect molecular gas at mm wavelengths in significant samples of high redshift objects.

2.4 High Energy Astrophysics

R. Klein in collaboration with J. Arons and G. Jernigan has studied the accretion of matter onto magnetized neutron stars. Using sophisticated two-dimensional radiation hydrodynamic calculations, they have uncovered a collective phenomenon in the accretion column of the neutron star, photon bubble oscillations (PBO), that is connected to photon bubble instabilities. These oscillations appear in the power spectrum of the emitted bolometric luminosity at well defined frequencies with moderatley high Q. Klein, Arons and Jernigan have made detailed calculations comparing the results with recently discovered rapid variability quasi-periodic oscillations in low magnetized neutron stars observed with the Rossi XTE satellite, as well as the recently discovered bursting X-ray pulsar GRO- J1744-28. They find that the frequency of PBO as well as the amplitude and correlation with mass accretion rate matches the newest RXTE observations of low magnetized bulge sources such as Sco-X-1 remarkably well. Their calculations provide a natural explanation of the -5/3 power law spectrum that they have discovered for frequencies greater than 500 Hz in GRO-J1744-28. According to their calculations, the power law spectrum is a cascade of photon bubble turbulence in the accretion column. If borne out by future observations, the discovery of photon bubble oscillations (PBO) will serve as a new probe of the physics near the surface of a neutron star and allow a determination of the surface magnetic field as well as mass accretion rate and accretion column geometry for a wide range of X-ray emitting neutron stars. In related work, Klein in collaboration with Jernigan and Arons has obtained time on Nasa's X-ray satellite RXTE to search for photon bubble oscillations in high luminosity X-ray pulsars.

R. Klein, in collaboration with postdocs S. Murray and T. Woods, and J. Castor and C. McKee has finished up a study of radiation hydrodynamic models of accretion disk coronae and winds in X-ray binary systems. This past year, they compared their model calculations with Exosat observations of X1822-371 and S0921-630, two eclipsing systems which are well suited for direct tests of coronal structure. They found that excellent fits to the eclipses by the companion star could be made for models with intrinsic system luminosities $\sim 0.1L-edd$. They also studied the dynamical effects of radiation pressure, by studying several models of high luminosity near the Eddington limit.

C. Mauche detected quasi-coherent oscillations in the extreme ultraviolet flux of the dwarf nova SS Cygni during observations with the Extreme Ultraviolet Explorer satellite of the rise and plateau phases of an anomalous outburst in 1993 August and a normal outburst in 1994 June/July. On both occasions, the oscillation turned on during the rise to outburst and persisted throughout the observation. During the 1993 outburst, the period of the oscillation fell from 9.3 s to 7.5 s over an interval of 4.4 days; during the 1994 outburst, the period fell from 8.9 s to 7.19 s (the shortest period ever observed in SS Cyg, or any other dwarf nova) within less than a day, and then rose to 8.0 s over an interval of 8.0 days. For both outbursts, the period P of the oscillation was observed to correlate with the 75-120 Angstrom count rate IEUV according to P a IEUV-0.094. A magnetospheric model was considered to reproduce this variation and it was found that an effective high-order multipole field is required with a field strength at the surface of the white dwarf of 0.1-1 MG. Such a field strength is at the lower extreme of those measured or inferred for bona fide magnetic cataclysmic variables.

F. Paerels (Columbia Univ.), M. Hur (UC Berkeley), C. Mauche, and J. Heise (SRON) presented high-resolution spectroscopy of the stellar photospheric spectrum of the white dwarf in the magnetic cataclysmic variable AM Herculis in the 75-120 Angstrom band obtained with the Short-Wavelength Spectrometer on the Extreme Ultraviolet Explorer. They positively detected ionization edges and absorption lines from highly ionized neon (Ne VI, Ne VIII). Surprisingly, they did not detect absorption at the O VI 2s, 2p edges, which were expected to be the strongest spectral features in this band in an atmosphere of solar composition at the density and temperature expected for the accretion region in this object. There is evidence for limb brightening of the spectrum in egress from eclipse, indicating the presence of a temperature inversion in the X-ray/EUV photosphere. The EUV spectra were interpreted in the context of the classical model for the soft X-ray/EUV emission from AM Her: hard X-ray irradiation of the atmosphere by the accretion shock.

K. Long (STScI), C. Mauche, J. Raymond (CfA), P. Szkody (Univ. of Washington), and J. Mattei (AAVSO) observed the dwarf nova U Geminorum during the peak and decline phases of a wide outburst in 1993 December with the Extreme Ultraviolet Explorer satellite. At peak, U Gem was one of the brightest EUV sources on the sky. The spectrum of the source is complex. Fitting the continuum to a blackbody, the apparent temperature at peak is $\sim 140{,}000K$, the luminosity is $\sim 4x10^{34}(d/90pc)^2 ergss^{-1}$, and the minimum size of the emitting region is comparable to that of the white dwarf. If the EUV emission arises primarily from the boundary layer between the accretion disk and surface of the white dwarf, then the boundary layer luminosity of U Gem is comparable to the disk luminosity. The EUV source is partially eclipsed at orbital phases 0.6-0.8. The eclipse spectrum, which we associate with a wind emerging from the vicinity of the white dwarf, is dominated by emission features. The identification of these emission features with transitions expected in a relatively cool $(T<160{,}000K)$, photoionized plasma helps to resolve a controversy concerning the ionization state of the winds of dwarf novae. The EUV lines arise from the dominant ionization states of the wind, and their strengths suggest that the mass-loss rate of the wind, at least in U Gem, is a substantial fraction of the accretion rate onto the white dwarf.

I. Shlosman (Univ. Kentucky), P. Vitello, and C. Mauche modeled the ultraviolet emission lines of the eclipsing nova-like variable V347 Puppis using a three dimensional kinematic and radiation transfer model. They showed that the narrowing of the UV emission lines during eclipse can be understood as the eclipse by the secondary of the innermost part of the accretion disk wind and the resulting reduction in the contribution of rotational broadening to the width of the lines. During the eclipse, the residual line flux is very sensitive to the maximum temperature of disk radiation. Good fits were obtained for reasonable mass-loss rates for maximum disk temperatures of 50,000 K. This constraint was imposed either by leveling off the inner disk temperature profiles, in agreement with recent observations of some nova-like variables, or by assuming that the accretion disk does not extend to the surface of the white dwarf, in which case V347 Pup is an intermediate polar. In anticipation of high-speed spectrophotometry of cataclysmic variables by the Hubble Space Telescope, they provided a numerical model of a timeresolved eclipse of V347 Pup or similar such system to be verified by future observations.

H. S. Park and her collaborators are conducting a gamma ray burst (GRB) optical counterpart search using an automated telescope system triggered by the Compton Gamma Ray Observatory's BATSE detector. The origin of GRBs is unknown, BATSE confirmed that they are isotropically distributed in galactic coordinates excluding the more plausible theories of neutron star origins. Due to the short duration of GRBs and the large angular error of the BATSE gamma ray detector, it is difficult to identify counterparts at other wavelenths. The LOTIS (Livermore Optical Transient Imaging System) experiment is connected to the BATSE real-time coordinate distribution network which transmits the GRB coordinates within 5.5 sec from the start of a GRB. The LOTIS system consists of 4 cameras each with 2048 x 2048 CCDs and a commercial f/1.8 telephoto lens with a 200 mm focal length. The total field of view is 17.6 x 17.6 degrees; the average slewing time is 4 5 sec; and its sensitivity is Mv 14 with a 5 sec exposure. Routine observation has begun as of October 1996 with the hope of detecting optical signals while the GRBs are still in progress. The LOTIS is a collaboration beteewn LLNL, NASA/Goddard, NASA/Marshall, UC San Diego, and Clemson University.

S. Marshall has joined a collaborative effort between the University of Michigan, LLNL, LANL, and UCSD which is dubbed ROTSE for ''Robotic Optical Transient Search Experiment.'' This program will search for astrophysical optical transients on time scales of a fraction of a second to a few hours. The initial goal is to find optical counterparts of gamma-ray bursts. ROTSE will use telemetry data from NASA satellites such as the Compton Gamma-Ray Observatory (CGRO) and the High Energy Transient Experiment (HETE) to direct an array of optical detectors toward GRB events within 10 seconds of the burst onset. A second search mode is also being developed that will allow detection of occultation of background stars by objects in the Solar system's Kuiper Belt. This second mode is intended to provide a census of the Kuiper Belt for objects as small as 3 km. The first phase of this project, ROTSE-I, will comprise a 2x2 array of wide field cameras with 200 mm, f/1.8, telephoto lenses on a fast slewing mount. Construction of ROTSE-I is underway at LLNL and Michigan with siting planned at the MILAGRO site in Fenton Hill, NM. The second phase (ROTSE-II) will utilize custom designed 45 cm aperture telescopes and is currently being designed.

E. Moran and D. Helfand (Columbia) have studied the $z=4.30$ quasar 1508+5714 with the ASCA X-ray Observatory, which represents the first detailed X-ray investigation of an object with $z>4$. Its spectrum in the 0.5–10 keV band (corresponding to the 3–53 keV range in the rest frame of the quasar) is well fitted by a single power law with an energy spectral index $\alpha_x=0.4$. Despite the similarity of this spectrum to that of the cosmic X-ray background, a break corresponding to the 40 keV turnover observed in the XRB spectrum is not present, reinforcing claims that quasars are not primarily responsible for the XRB.

E. Moran, M. Lehnert (Leiden), and D. Helfand (Columbia) have investigated the hard X-ray spectra of starburst galaxies with ASCA. The spectra of the nearby, luminous starbursts M82 and NGC 3256 both contain a hard power law component which dominates the X-ray flux above 2 keV. Although similar to the hard X-ray spectra of Seyfert galaxies, the most plausible origin of their hard X-rays is inverse-Compton emission, arising from the interaction of the copious far-infrared photon flux and supernova-generated relativistic electrons in the nuclei of these objects. In combination with other studies, it is becoming clear that a hard X-ray component is ubiquitous in the spectra of starburst galaxies. In the inverse-Compton scenario, starburst galaxies can produce a significant fraction of the cosmic X-ray background in the 2–10 keV band.

P. Vitello has continued his research on line-radiation winds from accretion disks. In collaboration with I. Shlosman and C. Mauche he has done detailed synthetic line modeling of rotating winds from the accretion disk in the cataclysmic variable V347 Puppis. Modeling was done using a kinematic model for the wind. This work showed the necessity of rotational broadening in the wind model, which clearly indicates a disk source for the wind. P. Vitello has also continued to develop with I. Shlosman a 2D time-dependent line-radiation pressure drive disk wind model which would remove many of the constraints of the kinetic wind model.

2.5 Interstellar Medium and Star Formation

R. Klein in collaboration with C. McKee and two graduate students at UC Berkeley, R. Fisher and V. Hilliard, is developing a fully adaptive mesh refinement three-dimensional magneto-hydrodynamics code for studies of interstellar gas dynamics. The code is based on high resolution Godunov methods in hydrodynamics and will permit large dynamic range in scale to be investigated for a variety of problems that treat the full dynamics of the magnetic field in detail. This code will permit MHD studies in the interstellar medium of unprecedented detail. In addition, Klein in collaboration with McKee and J. Stone of the University of Maryland and graduate students, has obtained a large grant from NCSA on the parallel CM-5 supercomputer to investigate three- dimensional magneto-hydrodynamical phenomena associated with the interaction of supernova shocks with magnetized interstellar clouds. These studies will be the next step in the work of Klein and McKee to study shock cloud interactions. They have previously investigated this interaction with magnetic fields in two-dimensions. The addition of the third dimension in the current work can be expected to show up important 3D effects of MHD instabilities and in addition permit them to investigate different field geometries not possible with two dimensions.

R. Klein in collaboration with T. Woods of SSL and LLNL has completed work on hydrodynamcal studies of interstellar cloud collisions. They have found that for clouds with initial surface perturbations, the collision initiates a strongly non-linear instability known as the bending mode or non-linear thin shell instability. They have demonstrated that in the near non-linear regime, the results are in excellent agreement with the analysis of Vishniac for weakly non-linear perturbations. They have shown that in the far non-linear regime this instability has a severe global affect on the merger of colliding clouds resulting in the development of elongated filamentary structure in the merged cloud system. The filamentary structure renders the merged cloud system highly porous. These results may have important implications for the mechanisms by which filamentary structure develops in the interstellar medium, in addition to placing strong limitations on coelescence theories of star formation.

R. Klein in collaboration with C. McKee and graduate student K. Truelove has obtained a large grant of supercomputer time on the Pittsburg C-90 supercomputer. Using a new self-gravitating three-dimensional adaptive mesh refinement hydrodynamics code that they have developed in collaboration with L. Howell and J. Greenough at LBL they are studying the collapse and fragmentation of molecular clouds that have initial perturbations. As result of the use of adaptive mesh refnement, they have been able to achieve collapse over a larger dynamic range of density (1 billion) and space (10 thouand) than has ever been possible. These new calculations of a thermally supported rotating cloud develop structure that is in disagreement with previous studies. Klein, McKee and Truelove have shown that with adaptive mesh refinement they are able to get to resolution far beyond previous studies and that this refinement is essential to keeping numerical noise on the discrete grid from undergoing substantial growth and lead to false fragmentation of the cloud. They have developed a new hydrodynamic criterion related to the Jeans condition that must be satisified by the grid at all times to ensure a physically correct result. They have demonstrated that much of the work in the past has violated this stringent condition required of the grid and as a result has led to erroneous evolution and fragmentation of the collapsing cloud. This work has progressed to the point that they are now able to start with a very varied set of initial conditions and determine the evolution to a high degree of accuracy. This will permit a complete study of how initial conditions actually influence the eventual outcome of star formation without the calculations being corrupted by numerical perturbations leading to false conclusions regarding fragmentation.

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

2.6 Stars, Stellar Evolution, and Supernovae

D. Alves correlated known LMC Planetary Nebulae (PN) with the Macho photometry database and searched for variability. One of fifty PN inspected, Jacoby-5, was found to be variable on short timescales and largely achromatic. This peculiar behavior may be due to Fe emission lines originating in high density regions of the nebula. Follow-up spectroscopic observations in collaboration with Mike Dopita of the Mt. Stromlo Observatory in Australia are planned. Macho data including the Cepheid pulsation mass histogram, the total number of clump giants, and the number of Asymptotic Giant Branch (AGB) red variables were used to constrain monte-carlo models of the star formation history of the LMC, revealing a burst approximately 50 million years ago. When the number of PN was added as an additional constraint, a burst 2-3 Gyr ago became highly probable, in good agreement with cluster dating techniques and recent HST results on the chemical enrichment of the LMC. Future work includes a more detailed investigation of the AGB red variables using theoretical evolutionary tracks provided by Peter Wood of the Mt. Stromlo Observatory in Australia.

B. Macintosh (LLNL) in collaboration with E. Becklin, B. Zuckerman and I. McLean (UCLA) has been carrying out a near-infrared search for brown dwarf companions to low-mass members of the Hyades and Pleiades cluster. Although no brown dwarfs have been discovered, the unmatched sensitivity of the Keck telescope, and the well-determined age of these clusters, allows the placing of strong upper limits on the frequency of occurence of brown dwarfs in these clusters. In addition, several low-mass stellar companions have been found, and their orbital distribution shows a deficit of wide binary systems, showing that such systems are disrupted by close stellar encounters in dense young clusters.

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

2.7 Solar System

W. J. Nellis, S. T. Weir, N. C. Holmes, M. Ross, and A. C. Mitchell demonstrated the existence of metallic hydrogen at pressures that occur in the interior of Jupiter. Electrical conductivities and shock temperatures were measured for shock-compressed liquid H_2 and D_2. Conductivites were measured at pressures of 93-180 GPa (0.93-1.8 Mbar) using dynamic compression. Calculated temperatures were in the range 2000-4000 K. The resistivity data are interpreted in terms of a continuous transition from a semiconducting to metallic, primarily diatomic fluid at 140 GPa and 3000 K. Shock temperatures up to 5200 K were measured at pressures up to 83 GPa. These data are interpreted in terms of a continuous dissociative phase transition above 20 GPa. The continuous transition from a molecular to monatomic fluid means that Jupiter has no distinct core-mantle boundary. The dissociation model derived from the temperature measurements indicates a dissociation fraction of about 0.05 at 140 GPa and 3000 K. The isentrope of hydrogen was calculated starting from the surface temperature of Jupiter (165 K). At a metallization pressure of 140 GPa in Jupiter, the temperature is about 4000 K and about 10conductivity was calculated along this Jovian isentrope by deriving a scaling relationship from the measured conductivities. The results indicate that hydrogen becomes metallic much closer to the surface of Jupiter than thought previously, a possible explanation of the very large magnetic field ($\sim$20 times larger than that of Earth). The larger radius below which hydrogen becomes metallic means that Jupiter contains about 50 more Earth masses of metallic hydrogen than thought previously. However, the value of the metallic conductivity of the molecular fluid is two orders of magnitude lower than predicted previously for the monatomic fluid, which is expected to exist deeper inside Jupiter and not to contribute significantly to the external magnetic field.

B. Macintosh, C. Max., D. Gavel, S. Gibbard (LLNL), I. DePater (UC Berkeley), and A. Ghez (UCLA) have taken high-resolution infrared speckle images at the Keck telescope of Jupiter's moon Io, Saturn's moon Titan, and Neptune. Speckle processing of these images to remove the effects of atmospheric turbulence makes possible an angular resolution of .05 arcseconds. The images of Io, consisting of four sets of 100 speckle frames, have been processed using bispectral methods into a high-resolution map of the moon showing three distinct volcanic regions (hotspots). These images may ultimately allow correlation of infrared emissions with surface features seen by Galileo to within a few kilometers. Images of Titan were taken in the K' band (2.1μ), which is able to penetrate Titan's methane clouds to the surface.

High-contrast features are observed at a resolution of 140 km/pixel, twice as good as the resolution of Titan images from the Hubble Space Telescope. These images should help to identify the composition of Titan's surface, which may have regions covered by water ice and/or liquid hydrocarbons. Images from Neptune are expected to show cloud features, which vary over timescales of hours to years. Knowledge of how these features evolve over time is of fundamental importance in understanding the basic mechanisms which drive the weather on Neptune and other planets, including the Earth.

2.8 Instrumentation

The LLNL laser guide star adaptive optics team, led by C. Max has continued to operate a prototype adaptive optics system on the 3-m telescope at Lick observatory. The system is optimized for operation in the near-infrared (1-2.5 microns), with 36 actively controlled subapertures on an LLNL-built deformable mirror. Using bright natural guide stars the system easily achieves near-diffraction limited performance in the near infrared, with a FWHM of 0.2 arcseconds in the K (2.2 micron) band and Strehl ratio improvement factors of 10-20.

The most significant devlopment has been the integration of a sodium laser guide star into the system. A team led by H. Friedman (LLNL) installed a 20-W pulsed dye laser on the Lick 3-m telescope, which produces a 9th magnitude artificial guide star in the atmospheric sodium layer at a height of 95 km. The adaptive optics system has been upgraded to take advantage of this guide star and to deal with the subtle optical differences between a natural guide star at infinity and the sodium star only 95 km away. In October of 1996 the first high-order corrected sodium laser guide star adaptive optics image from any telescope was produced, with a diffraction-limited core and Strehl ratio of 0.1 at 2.2 microns. This opens up nearly the whole sky to diffraction-limited observations, and will allow adaptive optics studies of such faint extragalactic objects. Scientific projects, planned in collaboration with J. Graham (UC Berkeley), A. Ghez (UCLA), E. Becklin (UCLA) and Bruce Macintosh (IGPP-LLNL) include studies of the host galaxies of active galactic nucleii, studies of young stellar objects, and searches for brown dwarf companions to faint stars.

Collaborators on the adaptive optics project include J. An, K. Avicola, B. Beeman, H. Bissinger, J. Brase, D. Gavel, B. Macintosh, S. Olivier, K. Waltjen, and J. Watson (LLNL.) This LLNL group is also involved in building the wavefront control subsystem and laser guide star for the planned adaptive optics system on the 10-m W.M. Keck telescope.

K. Ziock has continued his work with the Stellar X-Ray Polarimeter (SXRP) collaboration. The flight model of the SXRP has successfully undergone calibration at LLNL. SXRP is one of the focal plane instruments of the SODART telescope on the Russian Spectra X-Gamma mission which is expected to launch in 1998. It is the only x-ray polarimeter currently planned for a major x-ray mission. The LLNL contribution to SXRP includes manufacture and calibration of the two polarizer elements, a large mosaic graphite crystal for Bragg reflection of 2.6 and 5.2 keV x-rays and a 3 cm by 7 cm lithium cylinder for Thompson scattering of the x-ray continuum above 4 keV. The instrument calibration was carried out in a dedicated facility constructed for this purpose. Calibration included exposing the instrument to pencil beams of x-rays at different offsets and angles to fully simulate the converging SODART beam. Measurements were taken with both polarized and unpolarized x-ray beams appropriate to both polarizer elements. Preliminary analysis of the data indicates the instrument performs as advertised. The modulation factors measured with the polarized beams were as expected while the residual polarizations measured with the unpolarized beams were of order one percent.

GRATIS, the Gamma-Ray Arcminute Telescope Imaging System was successfully flown during the scientific ballooning campaign conducted from Alice Springs, Australia, last Fall. This flight represents the third of the telescope which was constructed by LLNL with collaboration from UCSB and UCB. The instrument was at altitude for over 24 hours with observations of more than 10 targets. The primary targets were clustered in the galactic center. Analysis of the data is in progress.

K. Ziock is collaborating on the development of a gamma-ray burst detector (GRBM) to restore the third interplanetary network for gamma-ray burst detection. A prototype has been delivered and integrated with the PGS instrument of the Russian Mars-96 mission. This spacecraft is scheduled for launch in November of 1996. The instrument is a joint effort of LLNL, GSFC, UCB's SSL and our Russian hosts at IKI. The instrument was designed with a minimalist philosophy to reduce its impact on interplanetary missions. It weighs 1000 gms, and consumes only 500 mW of power to run its electronics. The telemetry rate is variable with a minimum scientific return at 9.3 b/s. The third interplanetary network will consist of the Ulysses spacecraft, which is in a polar orbit of the sun, GRBM at Mars and any of a number of instruments in near Earth orbit. It will provide gamma-ray burst positions with arcminute error circles using arrival time triangulation at the three spacecraft. To achieve this accuracy requires correlating the burst light curves to $\sim 50ms$. In addition to gamma-ray burst detection, the GRBM detector includes a plastic scintillator component for detection of the charged particle flux. The instrument sensitivity is expected to be comparable to that of the Ulysses detector and should detect $\sim$50 bursts/year. The LLNL contribution to the project included construction and calibration of the detector assembly as well as overall mechanical design of the instrument.

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