

Columbia University
Department of Astronomy/Department of Physics
New York, New York 10027

This report covers the period September 2000 through August 2001 and comprises an account of astronomical research carried out in the Department of Astronomy and the Department of Physics.

Faculty and Research Associates were James Applegate, Elena Aprile, Norman Baker, Marcella Carollo, Arlin Crotts, Karl-Ludwig Giboni, Eric Gotthelf, Charles Hailey, Jules Halpern, David Helfand, Lam Hui, Steven Kahn, Laura Kay (Barnard), Dani Maoz (Visiting Professor), Lloyd Motz (Emeritus), Reshmi Mukherjee (Barnard), Robert Novick (Emeritus), Frederik Paerels, Joseph Patterson, Kevin Prendergast (Emeritus), Andrew Rasmussen, Malvin Ruderman, Daniel Savin, Edward Spiegel, Jacqueline van Gorkom and David Windt. Faculty members at Biosphere 2 are Karen Vanlandingham, Philip Yecko and Catharine Garmany.

Graduate students participating in research were Douglas Bramel, Tzu-Ching Chang, Aeree Chung, James Chonko, Jean Cottam, Alessandro Curioni, Chad Finley, Akimi Fujita, Mario Jimenez-Garate, Stefano Giovanardi, Eilat Glikman, JaeSub Hong, Miranda Jackson, Moo Kwang (Ryan) Joung, John Keck, Ali Kinkhabwala, Tomotake Kozu, Maurice Leutenegger, Yuexing Li, Adam Lidz, Nestor Mirabal, Kaya Mori, Tony Mroczkowski, Don Neill, Kaixuan Ni, Ian Mulvany, John Peterson, Jacob Noel-Storr, Masao Sako, Ben Sugerman, Robert Uglesich, Chuanyi Yang, Haitao Yu, Jun Zhang.

Undergraduates participating in research were Marcel Agueros, Eve Armstrong, Tiffany Christatos (Barnard), Maya Cohen (Barnard), Benjamin Collins, Catherine Espaillat, Yosi Gelfand, Elise Laird, Eve Locastro (Barnard), Rachel Semple Schuchter (Barnard), Dana Stern (Barnard), Gisela Telis.

Jean Cottam, Mario Jimenez-Garate, John Keck, Masao Sako received Ph.D. degrees.

Appointments during 2000–2001 were held by Adjunct Professors Michael Allison, and Michael Shara and Mordecai MacLow from the American Museum of Natural History (see their annual report). Postdoctoral Research Scientists Edward Baltz, Ehud Behar, Fernando Camilo, Christina Chiappini, Catherine Cress, Jason Koglin, Richard Easther, Masanori Kobayashi, William Kinney, Uwe Oberlack, Stephen Lawrence, Caleb Scharf and Jacob Vink

Van Gorkom continued as Chair of the Astronomy Department, Paerels as Director of the Columbia Astrophysics Laboratory and Kahn as Chair of the Physics Department.

1 Stars, Stellar Evolution, & Planets

Michael Allison of the NASA/Goddard Institute for Space Studies serves as a department adjunct, teaching a graduate level course in Planetary Fluid Dynamics. His research is devoted to the dynamics of planetary atmospheres. He is presently serving as a co-investigator on the Huygens Doppler Wind Experiment, designed to provide an in situ measurement of the Titan atmospheric circulation. He has also recently been added as a team member for the Cassini RADAR investigation for work on Saturn radiometry. In the past year, Allison worked with David Atkinson (University of Idaho) on a wave-dynamical interpretation of residual fluctuations in the Gaileo probe Doppler tracking. The results published by Allison and Atkinson (2001) imply a stable stratification in Jupiter's deep wind layer consistent with probe temperature-pressure data and the diagnostic analysis of the dispersive properties of cloud-top features.

Observations of field RR Lyrae variables are being made (using Biosphere 2 Observatory and the MDM 1.3 meter) by Yecko and used to constrain RR Lyrae models. The models are produced using a hydrodynamic code that incorporates turbulent convection and which has been very successful in reproducing the blue and red edges of the Cepheid instability strip and in modeling double mode Cepheids and RR Lyrae. Recent studies have recognized that the observed luminosities and effective temperatures in the RR Lyra instability strip differ from the predictions of models, but it is not known why. The goal of our observations is to produce detailed models of selected field RR Lyrae, especially double mode pulsators, to constrain model parameters and, it is hoped, resolve the discrepancy between model and data. Early results indicate that the discrepancy is due to a nonlinear amplitude effect and therefore absent from the linear blue and red edge model predictions. This work will continue with the participation of new Universe Semester students.

Starting July 1st as a research fellow at AMNH Neill began his study of cataclysmic variable (CV) star populations in collaboration with his thesis advisor Shara. This research is proceeding along four avenues of inquiry: 1. A study of the CV population in our Galaxy (the Milky Way) using observations taken with the 8K mosaic camera on the Hiltner 2.4m telescope, to characterize the population of low-amplitude, low luminosity cataclysmic variables (CVs) predicted to be numerous by current theories of CV formation and evolution (this study will examine 300,000 stars and has already yielded eclipsing binary stars at a rate of one per thousand), 2. A focused study of a CV in a globular

cluster using the Calypso Observatory 1.4m telescope and its High Resolution Camera which has yielded the first orbital period for a CV in a globular cluster and will help determine how CVs form in cluster environments, 3. A nova survey in the galaxy M81 using the Calypso Observatory 1.4m telescope and its Wide Field Camera which will have unprecedented time and spatial coverage allowing the first unambiguous determination of the nova rate and spatial distribution for any galaxy, and 4. A search for novae between the galaxies of the Fornax Galaxy Cluster which will provide a direct observation of the intra-cluster stellar content in this cluster and help constrain models of galaxy cluster formation.

The Center for Backyard Astrophysics accumulated ~ 800 nights of observation during 2000-1. This is a network of astronomers, primarily amateur, who do stellar photometry with small telescopes in their backyards. Columbia personnel included J. Patterson, J. Kemp, and C. Espaillat. We typically observe a star steadily for a few months, trying to amass the densest possible coverage by stressing long observation and distribution of observers in longitude. This provides a time series well suited to the study of periodic signals, and immunized from the “aliasing” problems inherent in data from a single site. Our long-time observers are in Belgium, Denmark, Maryland, Arizona, Illinois, New Zealand, South Africa, and Australia. During this period, new nodes were established in Finland, Canada, New Mexico, and Colorado. Most programs involve the study of cataclysmic variables, justly famous for the many periods present in their light curves.

Two particularly interesting results came from intense coverage of V803 Cen and HP Lib, two well-known CVs with a spectrum dominated by helium. We found “superhumps” in the light curves during their bright states; and by accumulating a long baseline of observations with no aliasing, we managed to resolve the orbital and the superhump periods with high precision measures. For V803 Cen, the latter is only 0.4% longer than P_{orb} , which implies a secondary (mass-losing) star of only 0.014 ± 0.009 Mo. Since the secondary is now losing mass at $\sim 10^{-10}$ Mo/yr, this implies that it is evaporating on a timescale of 10x years.

By studying the precession rates of CVs and X-ray binaries of known mass ratio, we established a universal calibration between the (observable) precession rate and the (generally unobservable) mass ratio in such stars. This essentially permits us to weigh the unseen secondary star. By applying the relation to the 66 CVs showing superhumps, we found a well-constrained mass-radius relation for the secondaries, and identified 7 as clearly below the Kumar limit of 0.075 Mo.

Large data sets, comprising typically ~ 300 hr over ~ 60 nights, have been collected on many other short-period stars, to study accretion-disk precession in CVs. Their study and understanding will keep us busy for years to come.

Scharf, together with Storrie-Lombardi (JPL) and McDonald (JPL) has investigated the constraints on

sites of astrobiological interest in the Galaxy through the presence of Phosphorus. They find an intriguing, and new, prediction that 1 in 5 star systems, on average may have the capacity for a terrestrial sized biomass.

2 X-ray & γ -ray Sources

Along with Q.D. Wang and C.C. Lang (U. Mass), Gotthelf has obtained the complete set of data comprising the “UMass/Columbia Galactic Center *Chandra* Survey”. This is the first large-scale, high spatial resolution (arcsec) X-ray imaging-spectroscopy of the central $2^\circ \times 1^\circ$ of the Galaxy, mapped using 30×12 ks overlapping rastered pointings. This rich survey is intended to be widely exploited over the coming years, and is destined to become one of the great legacies of the *Chandra* program. Student Filip Jagodzinski is aiding in the reduction and analysis.

At low Galactic latitude, establishing the nature of the majority of the high-energy γ -ray sources discovered by the EGRET instrument on *CGRO* is a problem that continues to require intensive multiwavelength observational effort. The Columbia group made considerable progress this year by obtaining two probable neutron-star identifications. Halpern, Camilo, *et al.* discovered PSR J2229+6114, an energetic, 51.6 ms radio and X-ray pulsar in the error box of 3EG J2227+6122. Mirabal & Halpern discovered a weak, ultrasoft X-ray source that is the probable neutron-star counterpart of the brightest unidentified EGRET source at high Galactic latitude, 3EG J1835+5918. PSR J2229+6114 is second only to the Crab in spin-down power among γ -ray pulsars. Its overall spectral energy distribution indicates a possible maximum in the MeV range. Additional studies of its Vela-like synchrotron nebula are planned for *Chandra*. Camilo performed a deep radio-pulsar search of the 3EG J1835+5918 position, with negative results. With no optical counterpart to $V > 25$, this neutron star could be the next Geminga-type pulsar, and the prototype of the hypothesized Gould-belt pulsars that could be responsible for several weak EGRET sources at intermediate Galactic latitude. Further observations of it with *Chandra* and *HST* are scheduled. Camilo and collaborators found several possible energetic radio pulsar counterparts of additional EGRET sources in the Parkes Multibeam Survey. Multiwavelength work on more EGRET error boxes is in progress.

The MDM Observatory continues to pursue optical and infrared observations of afterglows of γ -ray bursts (GRBs) under the direction of Halpern and Mirabal. Several GRB locations were observed in 2000-2001. It is expected that the event rate will increase with the successful operation of the HETE-2 satellite. Images of successful observations of GRBs at MDM Observatory are maintained at: http://www.astro.columbia.edu/group_research.html.

Mukherjee and Bramel worked on STACEE (Solar Tower Air Cherenkov Effect Experiment), a ground-based detector that is sensitive to high energy gamma-

rays in the regime 50 to 300 GeV. This part of the electromagnetic spectrum has been largely unexplored and astrophysics in this energy range promises exciting scientific returns. STACEE has detected the Crab nebula, and the active galaxy Markarian 421, thus demonstrating that lower energy thresholds can be achieved by using existing large arrays of solar heliostat mirrors to collect Cherenkov light.

Mukherjee, Gotthelf, Halpern, and Mirabal, and undergraduate Dana Stern worked on unidentified EGRET sources, specifically the sources 3EG J2016+3657 and 3EG J1621+8203. The former is a blazar and the latter is most likely the second radio galaxy to be detected by EGRET. Work on several of these mysterious unidentified high energy sources is currently in progress, and is part of Dana Stern's undergraduate thesis research.

Paerels, Helfand, and students Telis and Sako devised and carried out a very simple, definitive experiment to search for intergalactic dust. Extinction by such dust could complicate the cosmological interpretation of the Hubble Diagram for type Ia Supernovae. They obtained the deepest-ever X-ray image of a very distant quasar with the Chandra X-ray Observatory, reasoning that scattering of X-rays by dust particles in the intergalactic medium would produce a bright halo around the quasar. No such halo was found, and the absence of a halo definitively rules out extinction of light by intergalactic dust as an explanation for the rapid dimming of distant supernovae with distance: the acceleration of the expansion of the Universe is real. Careful analysis of the X-ray image will produce an upper limit on the density of intergalactic dust, which will be crucial in future attempts to measure the properties of the Dark Energy from the precise history of the rate of acceleration of the Universe.

3 Pulsars, Neutron Stars, & Supernovae

Hailey and graduate student Mori have been conducting neutron star research. They have developed a novel method for determining the X-ray line emission and oscillator strength for elements and ions in ultra-strong magnetic fields. The method is computationally extremely fast. Thus non-hydrogenic neutron star atmospheres can be systematically addressed for the first time. Their new theoretical approach has been accepted for publication in ApJ (astro-ph/0109214). They are planning to analyze Chandra data on RXJ 185635-3754 with this atomic physics model. Along with Frits Paerels they are also studying Newton RGS data on the Vela pulsar.

Helfand, Agueros, and Gotthelf completed the analysis of XMM-Newton observations of the composite supernova remnant G16.7+0.1. The remnant's synchrotron core is detected in X-rays for the first time. The X-ray-to-radio flux ratio for the object is intermediate between that of the youngest Crab-like objects and the 10^4 yr-old Vela remnant.

Helfand, Collins, and Gotthelf completed an analysis of Chandra observations of the composite supernova

remnant G29.7-0.3. This remnant houses the youngest known pulsar in the galaxy (age ~ 700 yrs). Their detailed spatially resolved spectral analysis suggests that, despite its currently slow rotation period of over 300 msec, the pulsar may have been born spinning rapidly ($P \sim 3$ msec); the object's huge magnetic field ($B \sim 5 \times 10^{13}$ G) would have led to the loss of nearly 10^{52} ergs of rotational kinetic energy which could have powered the rapid expansion of the remnant shell, helping to explain its enormous size.

Helfand and P. Slane (SAO) have analyzed the Chandra ACIS data on the putative remnant of the supernova of 1181 AD, 3C58. They find the surface temperature of the newly discovered pulsar in the center of the remnant to be a factor of at least 30 below that predicted by standard neutron star cooling calculations for an 800-year old star, implying either that the association of the remnant with SN1181 is incorrect, or that exotic cooling mechanisms must be at work.

Gotthelf continues his investigations into the connection between young neutron stars and supernova remnants (SNR). With various collaborators, he has obtained *Chandra* data on eight pulsar/SNR associations, which are currently being analyzed. These objects reveal, for the first time, wisps, co-aligned toroidal structures, and axial jets resolved in X-rays on arc-second scales, similar to optical features in the Crab nebula. These structures are found to be ubiquitous among young rotation-powered pulsars; collectively they provide evidence of a fundamental morphological and spectral relationship between the complex wind nebula structure and the central engine in young rotation-powered pulsars. Student Charles Olbert is participating in this study.

Helfand, Halpern, and Gotthelf will continue to observe the Vela pulsar and changes in its synchrotron nebula with *Chandra*. Spectacular asymmetric toroidal arcs and axial jets show variations in just one month, similar to the moving structures in the Crab nebula. Models involving relativistic post-shock flow in a magnetized pulsar wind are being investigated.

The young, distant, SNRs Kes 75 and G11.2-0.3 are remarkably similar, bright shell-type SNRs with central pulsars, but their timing properties are unique. The 324 ms pulsar PSR J1846-0258 in Kes 75 is exceptional: its period and spin-down rate are each 10 times greater than that of the Crab, most likely a result of its extreme magnetic field strength. PSR J1846-0258 has the youngest known spin-down age ($P/2\dot{P} \sim 700$ yr), which is coeval with Kes 75. In contrast, G11.2-0.3 contains the 69 ms pulsar PSR J1811-1926 with age 24,000 yr, in severe discrepancy with that of the SNR, which is proposed as the remnant of supernova SN 386. This suggests the intriguing possibility that PSR J1811-1926 was born spinning near its current rate or suffered an episode of rapid spin-down. Student Ben Collins is participating in this study.

Gotthelf is participating in a *Chandra* study of the Crab-like 16 ms pulsar PSR J0537-6910 in N157B, in

collaboration with Q.D. Wang (U. Mass). A point-source is embedded in a nebula morphologically similar to the Crab in shape and size, including evidence for a jet-like feature. A third distinct feature is a region of large-scale diffuse emission trailing the pulsar. This X-ray feature is likely powered by a toroidal pulsar wind of relativistic particles which is partially confined by the ram-pressure from the supersonic motion of the pulsar. A similar pulsar wind morphology is found in a newly acquired *Chandra* image of the radio pulsar PSR B1757–24, also known as “the Duck”. V. Kaspi *et al.* (McGill U.) report the first detection of X-ray emission from PSR B1757–24, and find a faint tail similar to that of PSR J0537–6910.

Gotthelf *et al.* (2001) reported the localization of the forward and reverse shock fronts in the young SNR Cas-A with *Chandra*. The remnant is found to have swept up roughly the same amount of mass as was ejected, suggesting that it is just entering the Sedov phase.

Gotthelf is also studying the long-term timing properties of several X-ray pulsars discovered over the last few years using *RXTE*. These include the 16 ms pulsar in N157B and the 50 ms pulsar PSR B0540–69, both of which reside in the Large Magellanic Cloud [collaboration with F. Marshall and W. Zhang (GSFC/NASA), J. Middleditch (LANL), & Q.D. Wang], the 7 s Anomalous X-ray Pulsar in the SNR Kes 73 [with V. Kaspi & D. Chakrabarty (MIT)], and the 324 ms pulsar in Kes 75 [with G. Vasisht (JPL), V. Kaspi, and K. Torii (Kanagawa U.)]. Together, these objects present a diverse sample of young pulsars to explore the revolution and evolution of young neutron stars.

Camilo continues to use the Parkes Multibeam Pulsar Survey, which is the deepest survey for young pulsars in the Galactic plane, for a number of investigations. These include studies of new pulsar/SNR associations, binary pulsars with massive companions, and radio pulsars with the highest magnetic fields. Camilo is participating in major investigations of the rich millisecond pulsar population of the globular cluster 47 Tucanae. These include the detection of an ionized interstellar medium in the cluster via the correlation between acceleration and pulsar dispersion, with P. Freire (U. Manchester), and a deep X-ray imaging study using *Chandra*, with J. Grindlay (Harvard).

In addition to survey work, Camilo is proposing deeper radio pulsar observations of X-ray discovered neutron stars which were heretofore considered radio quiet, in order to cover the wide range of radio luminosities which are seen among pulsars. In a pair of long observations with the Parkes telescope, he recently discovered an energetic, young, 135 ms pulsar in the oxygen-rich SNR G292.0+1.8, for which a likely pulsar wind nebula had been imaged by *Chandra*.

Maoz and students carried out a survey for faint, distant supernovae (SNe) in deep duplicate archival Hubble Space Telescope images of galaxy clusters (Gal-Yam, Maoz, & Sharon 2001). They discovered six SNe, with redshifts $0.18 \leq z \leq 0.98$ and $23 < I < 28$ mag, in 6 effective overlapping WFPC2 fields. This is the deepest

SN survey undertaken over more than one WFPC2 field. The field SNe were used to characterize for the first time, and to compare to model predictions, the SN counts at these faint levels. Interestingly, the counts are 2-5 times lower than some predictions. The SNe in the clusters were also used to derive for the first time a cluster SN-Ia rate. The rate, at a mean redshift of 0.41, is very similar to published field SN-Ia rates at such z , and comparable to the rate in local elliptical galaxies. This argues that the large mass of iron and the excess energy observed in the intra-cluster media of clusters was not produced by a population of SNe-Ia, as has been proposed.

Sugerman, Lawrence and Crofts developed a technique applying image subtraction to spatially resolved spectra in order to isolate subtle differences in a time series of STIS observations of Supernova 1987A. These have revealed a rapidly widening collection of “hot spots” due to the collision of ejecta of the original supernova explosion with pre-existing circumstellar nebula, particularly the inner, equatorial ring. These data cover the evolution of such interaction regions, from extremely early times, in the first case were a supernova remnant has been observed from the first moments of formation. They have also used this technique to make a complete study of changes in inner circumstellar ring, starting at times before the collision of the ejecta.

Phenomena and proposed models associated with the evolution of the surface magnetic field of spinning-down or spinning-up neutron stars have been re-examined by Ruderman leading to 1) a possible resolution of calculated excess heating for Vela-like pulsars; 2) two different glitch families encompassing the small Crab-like glitches and the giant Vela-like ones; 3) a proposed explanation for apparent free precession in some radiopulsars (astro-ph/1019533).

A more sensitive search for redshifted annihilation γ -rays from the Crab pulsar did not confirm previous discovery claims. An earlier theoretical model by Ruderman and Zhu (1997, ApJ, 478, 701) to account for such a feature seems likely to have filled a needed gap in the literature. (Ulmer et al. ApJ, 554, 244).

4 Active Galactic Nuclei

Halpern and M. Eracleous (Penn State U.) are continuing their long-term spectroscopic monitoring of very broad, double-peaked Balmer lines, which are found preferentially in radio-loud AGNs. The profiles of these double-peaked lines are highly variable on time scales of months to years, a behavior which can be exploited to evaluate models for their origin, and to study the dynamics of the accretion process in AGNs. Their recent work demonstrates that variability of the *shapes* of the emission lines must be due to dynamical motions, and cannot be explained by reverberation (light echo) effects. They also rejected the binary broad-line region hypothesis, and scenarios involving bloated stars or “clouds” in randomly inclined Keplerian orbits. Possibly cyclic behavior in several objects appears to favor dynamical or wave motions in the accretion disk

as the cause. A comparison study of the ultraviolet emission lines of some of these objects is underway with *HST*. New examples of double-peaked Balmer lines continue to be discovered, frequently in LINERs. An explanation of this association in terms of the ion torus (or advection-dominated accretion flow) was offered a decade ago, and continues to be attractive.

Leighly (U. Oklahoma) and Halpern will be obtaining *HST* and *Chandra* observations of a bright new QSO, PHL 1811, that was selected in the *FIRST* survey. At $V = 14$, and $z = 0.192$, it is one of the brightest and bluest QSOs, while having the optical emission lines of a Narrow-Line Seyfert 1 Galaxy, and almost no X-rays. Several alternative explanations for the weak X-ray emission from PHL 1811 were described in the discovery paper. It is expected that STIS spectra of its ultraviolet emission lines will be most helpful in determining the true reason.

5 Surveys

Helfand and his principal collaborators R. Becker (UC Davis) and R.L. White (STScI) completed the penultimate observing session for the *FIRST* survey with the VLA. To date, 8565 deg² have been mapped to a sensitivity threshold of 1 mJy at 20cm and 771,000 sources have been located with positional accuracies of better than 1".

Helfand and Glikman with their *FIRST* collaborators have continued their program to find highly reddened quasars using the 2MASS and *FIRST* catalogs. Spectra on over two dozen candidates have been obtained, yielding a success rate in excess of 50%. Of the first 10 quasars identified, two are strongly lensed, suggesting a re-evaluation of lensing statistics may be in order.

Helfand and F. Harrison (Caltech), have continued their major program to identify serendipitous faint X-ray sources in *Chandra* fields. To date, they have produced a catalog of over 500 X-ray sources detected in the 2-10 keV band in two dozen fields and have obtained deep ($R \sim 24 - 25$) optical images of all these fields. Over 200 spectroscopic redshifts have been obtained. Identifications include four Type II (heavily obscured) quasars, many more normal quasars, and a wide variety of active and apparently inactive galaxies. They are currently examining the variation in source surface density from field to field and, in collaboration with Scharf and B. Johnson, are beginning a program to correlate deep optical galaxy counts with both the detected X-ray source populations and the residual diffuse X-ray background.

Helfand and Chang in collaboration with Refregier (Cambridge) continued their attempts to extract a weak-lensing signal from the *FIRST* data. Significant progress has been made in developing a technique to extract the signal directly from the *uv* data, greatly simplifying the correction of systematic effects. A single simultaneous fit to the *uv* visibilities can now extract complete source parameters (flux density, size, shape, and position) for

the ~ 40 radio sources detected in each snapshot image. A linear algorithm to remove the effects of bandwidth smearing, time-averaging smearing, and variable synthesized beam effects has been tested successfully. Production runs on a supercomputer in Cambridge will be conducted in the coming year.

Helfand, along with Becker and White, have begun a major effort to construct a sensitive, high-dynamic range radio image of the Milky Way. Observations of a 13-degree strip of the plane in the VLA B-, C-, and D-configurations were completed and high dynamic-range images have been constructed. Data to create a 90 cm image of the same region has also been obtained and their analysis is in progress. In collaboration with a group from the University of Leicester, they have begun mapping the same region with the XMM-Newton observatory, providing a dramatic new view of stellar birth and death in the Galaxy.

Maoz, with student Eran Ofek, carried out a search for gravitationally lensed quasars in the *FIRST* catalog, in the large image-separation range expected from lensing by galaxy clusters. In collaboration with F. Prada and H.-W. Rix, all candidates were ruled out as lensed pairs (Ofek et al. 2001). This is one of the largest lensing surveys to date, with a source population of about 8000 quasars, and puts a strong upper limit on the large-separation lensing fraction. Analysis of this result will constrain cluster structure and evolution.

Maoz and collaborators carried out several studies of super star clusters (SSCs) with the Hubble Space Telescope (*HST*). SSCs are young, massive ($\sim 10^5 M_\odot$) clusters of stars that are probably bound, and which may eventually evolve into globular clusters. They are a dominant site for star formation in starburst environments, and are therefore important for interpreting observations of high-redshift galaxies and for understanding the formation of globular clusters. In Maoz et al. (2001a), UV through IR images of two nearby galaxies with circumnuclear starburst rings, taken with three different *HST* cameras, were analyzed to give one of the broadest wavelength views to date of SSCs and their environment. The luminosity and mass functions of the SSCs are power laws with index -2 , very similar to what is seen in merging galaxies and starburst dwarfs. This suggests that starbursts, regardless of specific environment, may share universal properties, and hence nearby starburst properties may indeed be representative of processes at high z . In this respect, it is noteworthy that in the nearby galaxies, line and continuum emission are poorly correlated due to patchy dust obscuration. Therefore, derivation of star formation rates in high- z starbursts based on either Balmer line flux or blue light may give incomplete pictures.

In a separate study Maoz, Ho, & Sternberg (2001b) analyzed long-slit *HST*-STIS spectra of the brightest SSC in the nearby dwarf irregular galaxy NGC 1569. Spatially resolving for the first time the stellar populations of a SSC, they showed that the Wolf-Rayet (WR) signatures previously seen in this cluster come exclu-

sively from a sub-cluster, NGC1569-A2, which may be completely separate. The observed equivalent widths of the WR emissions are larger than ever seen in any starburst clump, and much larger than model predictions for clusters with the sub-solar metallicity observed for the gas in this galaxy. Apart from the discrepancy with models, the results indicate sharp changes in metallicity or initial mass function between too adjacent and co-eval SSCs.

An ongoing VLA HI survey of galaxy clusters in the local universe is carried out by van Gorkom with Bravo-Alfaro (Guanajato), Dwarakanath (RRI, Bangalore), P. Guhathakurta (UCSC), B. Poggianti (Padova), D. Schiminovich (Caltech), M. Valluri (Chicago), M. Verheijen (NRAO), E. Wilcots (Wisconsin) and A. Zabludoff (Arizona). This year observations were made of A85 and A754 at $z=0.06$ and of A2192 at $z=0.2$. These data will be combined with deep multi color imaging and spectroscopy. A byproduct of the HI observations will be a deep radio continuum image of each of the clusters. This database will allow for a detailed study of the star formation history (and future) of galaxies of different morphological types, of the interaction and merger rate of the galaxies and of the dynamical state of the clusters. Examples of what can be done with this kind of data are the results on the Coma Cluster (Bravo-Alfaro et al 2000), where clear evidence for substructure is found from the HI data and on A2670 (Poggianti and van Gorkom, 2001). The study of A2670 is prototypical for the survey. The data base is identical to what has been obtained for clusters at intermediate redshift. In A2670 we also have information about the gas content, information which is lacking at intermediate z . Thus the survey will provide an ideal comparison sample for studies at intermediate redshift.

6 Galaxies & Large Scale Structure

Baltz and Gondolo (CWRU) calculated the expected rate of caustic crossing events in future pixel microlensing surveys. They found that these events would comprise a more significant fraction of the events than in classical microlensing surveys with resolved stars.

Baltz and Silk (Oxford) constructed an estimator useful in measuring the mass function of lenses in pixel lensing survey, where the Einstein timescales are often unmeasurable.

Baltz, Crotts and Gyuk (Adler Planetarium) have constructed a sophisticated model of microlensing in M31 in preparation for the analysis of the MEGA microlensing survey.

Baltz and Hui have investigated the microlensing of gamma ray burst afterglows. Of particular interest is the probability of these events, and they have considered several biases affecting this.

Considering the hypothesis that dark matter consists of supersymmetric partners of Standard Model particles, Baltz and Gondolo (CWRU) showed the measurement of the anomalous magnetic moment of the muon is quite promising. Assuming that the measured discrepancy is

due to a supersymmetric contribution, the dark matter detection rates in underground experiments are almost guaranteed to be accessible to the next generation of experiments. Mandic (Berkeley), Baltz and Gondolo (CWRU) explain the origin of this minimum cross section in supersymmetric models.

Baltz, Edsjö (Stockholm), Freese (Michigan) and Gondolo (CWRU) investigated the confirmation by the HEAT collaboration of the comic ray positron excess. For this to have a origin in supersymmetric dark matter annihilations, the galactic halo must be significantly clumped.

Baltz and Murayama (Berkeley) pointed out that simple models for the light gravitino to be warm dark matter have been ruled out by improving data from large scale structure and cosmic microwave background measurements. They then constructed a model that evades these constraints.

In collaboration with Stiavelli (STScI) and de Zeeuw (Leiden), Carollo has analysed data from an HST NICMOS-Cam2 near-infrared (NIR) survey in the J and H filters for a sample of 78 spiral galaxies. Concerning the properties of the photometrically-distinct ‘nuclei’ which are found embedded in most of the galaxies, this survey has shown that: *(i)* In the NIR, the nuclei embedded in the bright early- to intermediate-type galaxies span a much larger range in brightness than the nuclei which are typically found embedded in bulgeless late-type disks; *(ii)* Nuclei are found in both non-barred and barred hosts, in large-scale ($\gtrsim 1$ kpc) as well as in nuclear (up to a few 100pc) bars; *(iii)* There is a significant increase in half-light radius with increasing luminosity of the nucleus in the early/intermediate types (a decade in radius for ≈ 8 magnitudes brightening), a correlation which was found in the V band and which is also seen in the NIR data; *(iv)* The nuclei of early/intermediate-type spirals cover a large range of optical-NIR colors, from $V - H \approx -0.5$ to 3. Some nuclei are bluer and others redder than the surrounding galaxy, indicating the presence of activity or reddening by dust in many of these systems; *(v)* Some early/intermediate nuclei are elongated and/or slightly offset from the isophotal center of the host galaxy. On average, however, these nuclei appear as centered, star-cluster-like structures similar to those which are found in the late-type disks.

Concerning the underlying galactic light, the main result of the NICMOS survey is the startling similarity between the nuclear stellar cusp slopes $\langle \gamma \rangle$ in the near-infrared compared to those derived in the visual passband. This similarity has several implications: (1.) Despite the significant *local* color variations that are found in the nuclear regions of spirals, there are typically little or no optical-NIR *global* color gradients, and thus no global stellar population variations, inside ~ 50 -100 pc from the nucleus in nearby spirals. (2.) The large observed range of the strength of the nuclear stellar cusps seen in the HST optical study of spiral galaxies reflects a physical difference between galaxies, and is not an artifact caused by nuclear dust and/or recent star

formation. (3.) The dichotomy between $R^{1/4}$ bulges, with steep nuclear stellar cusps $\langle \gamma \rangle \sim 1$, and exponential bulges, with shallow nuclear stellar cusps $\langle \gamma \rangle < 0.3$, is also not an artifact of the effects of dust or recent star formation. (4) The presence of a surrounding massive disk appears to have no effect on the rise of the stellar density distribution within the innermost hundred pc of the $R^{1/4}$ spheroids. These results imply a breakdown within the family of exponential bulges of the nuclear versus global relationships that have been found for the $R^{1/4}$ spheroids. Such a breakdown is likely to have significant implications concerning the formation of exponential bulges and their connection with the $R^{1/4}$ spheroids.

In collaboration with Lilly (HIA), Carollo is continuing a program to measure emission line ratios in a selected sample of $0.5 < z < 1.0$ CFRS starforming galaxies in order to compute their Interstellar Medium metallicities. The latter are derived by means of the empirically-calibrated R_{23} estimator introduced by Pagel et al. (1979). In addition to the optical CFHT spectra discussed in Carollo & Lilly (2001), new J -band Keck spectroscopy of the $H\alpha$ and [NII]6583 lines were acquired for several objects. These lines allow one to break the degeneracy between low ($\lesssim 0.1 Z_{\odot}$) and high ($\gtrsim 0.5 Z_{\odot}$) metallicity of the R_{23} estimator, and have put on solid ground the finding that the $0.5 < z < 1.0$ blue galaxies with relatively high $L_{H\beta}$ are significantly metal-enriched ($Z \gtrsim 0.3 Z_{\odot}$ up to Z_{\odot}). Therefore, these results do not support previous suggestions in which the $0.5 < z < 1.0$ starforming galaxies are dwarf galaxies brightened by large bursts of star-formation, but support instead a picture where at least a significant fraction of them evolves to become today's massive metal-rich systems.

Crotts is leading an international collaboration to determine the rate of gravitational microlensing due to masses in the halo of M31, using the 8K camera built for MDM Observatory by himself, G. Luppino and several others. Observations at MDM, the KPNO 4-meter and Isaac Newton Telescope are beginning to reveal probable microlensing events at a high rate. Furthermore, a similarly high rate has been found in earlier data collected by Robert Uglesich at MDM and the Vatican Advanced Technology Telescope, and these results will be presented soon in his PhD thesis, as well as submitted for publication.

Fujita and Mac Low have continued their study of cosmological feedback and metal ejection from high-redshift dwarf galaxies. In the past year, they modeled the formation of dwarf galaxies and the effects of following starbursts in the galaxies, using ZEUS-3D, an astrophysical gas dynamics code. They are currently analyzing the results of the simulations. Fujita and Mac Low started to work on a project on the escape of ionizing radiation from dwarf starburst galaxies with Martin (Caltech) and Abel (Cambridge). The models of the galaxies are based on the above work, and they are interested in the role of dwarf starburst galaxies in ionizing the intergalactic gas.

A supermassive black hole will rip apart a star that strays within its tidal radius, causing an Eddington-limited UV/X-ray flare for several months as the orbiting debris accretes. While such events are predicted to occur once in $\sim 10^4$ yr per galaxy, an experiment was performed in 1990-91 that sampled hundreds of thousands of galaxies in the ideal wavelength band, *i.e.*, the *ROSAT* All-Sky Survey. Three galaxies had unusual X-ray flares, but no evidence for nuclear activity in ground-based spectra. To establish beyond a reasonable doubt that these were tidal disruption events, Halpern and collaborators are obtaining *HST* spectra to search for weak, permanent Seyfert activity, the only possible alternative to the disruption hypothesis. Establishing the UV/X-ray properties of genuine tidal disruption events is important for the next generation of sky surveys that will monitor millions of galaxies. Masses of black holes could be studied by monitoring the outburst light curves and the spectra of the tidal debris.

J. Hibbard (NRAO), van Gorkom, M. Rupen (NRAO) and Schiminovich (Caltech) assembled an HI Rogues Gallery, a collection of images of HI in weird galaxies and weird HI in otherwise normal galaxies. The atlas will appear in the proceedings of the conference on Gas and Galaxy Evolution (ASP 240) and will also be accessible on the web. It contains more than 180 systems.

Hui and collaborators have worked on a variety of projects in the last year. On the intergalactic medium and structure formation: they derived constraints on the baryon fraction, the amplitude of the primordial power spectrum and the temperature of the intergalactic medium from observations of quasar spectra at redshifts of a few. On galaxy large scale structure: they worked out the predictions of the halo model for the clustering properties of galaxies in real and redshift space, opening the way to include galaxy bias in a non-trivial but well-motivated way (*i.e.* nonlinear and stochastic); Lam Hui is also a member of the large scale structure working group of the Sloan Digital Sky Survey, and has contributed to the computation of the integral constraint correction in a series of recently published papers on the two-point correlation from the early released data. Finally, on extra-solar planets: Sara Seager and Lam Hui calculated the atmospheric lensing signal expected during extra-solar planetary transits. They also proposed a method to constrain the oblateness of planets by examining asymmetry in the transit light curves.

Neill and Hailey concluded their research into the dynamics of the galaxy cluster Abell 262 using a multi-object spectrograph and published the results in the *Astrophysical Journal*.

Scharf continued working with the WARPS (Wide Angle ROSAT Pointed Survey) collaboration to detect high redshift, X-ray clusters of galaxies with Ebeling (Hawaii), Jones (Birmingham) and Perlman (UMBC). Using a combination of Keck spectroscopy and Subaru infrared imaging the WARPS has this year identified several new clusters at redshifts greater than 0.7, including

the most massive, highest redshift cluster of galaxies currently known, at redshift 1.01, which also exhibits strong gravitational lens features. The WARPS also obtained new X-ray data from the Chandra and XMM observatories on 15 high redshift clusters. Scharf has worked on this data to determine X-ray gas temperatures and to constrain the high redshift evolution of clusters. Preliminary results provide independent verification of CMB and SNe measurements of a low density cosmology dominated by a cosmological constant.

Scharf and Donahue (STScI) completed work on the ROSAT Optical-X-ray survey of galaxy clusters. They have shown, for the first time, quantitative evidence for apparent biases in all cluster detection techniques, including X-ray. Key results have also been that the red-sequence detection method misses low mass clusters, and that the mass-to-light ratio in massive clusters is an increasing function of mass.

Scharf has obtained data from MDM for a new photometric galaxy redshift survey in the region of a speculated inter-cluster gas filament and is working to constrain the baryonic content of the “cosmic web” using this and new XMM data. In concert with this, a new spatial-spectral matched filter approach to mapping gas emission temperatures in X-ray data has been developed. The technique is computationally fast and optimized for faint sources of emission.

Chang, van Gorkom, A. Zabludoff and D. Zaritsky (Univ of Arizona) and C. Mihos (CWRU) completed a search for HI in a sample of E+A galaxies in the local universe in a variety of environments. The conclusion is that E+A galaxies have a wide range of HI properties. Limits on the radio continuum emission from these galaxies rule out that these are dust enshrouded starbursts. A follow up observation of the most HI rich system in the sample shows that the gas is very smoothly distributed and it is probably the low volume density of the gas that prevents the system from forming stars. In a similar study of E+A galaxies in the Coma Cluster Bravo-Alfaro, van Gorkom, V. Cayatte and C. Balkowski (Paris) obtained very low upper limits to the HI mass in these systems. In galaxy clusters removal of the gas is the most likely explanation that these galaxies stopped forming stars abruptly.

M. Balcells (IAC, Tenerife), van Gorkom, R. Sancisi (Bologna) and C. del Burgo (IAC) completed a paper on the HI distribution and kinematics in the shell elliptical NGC 3656. For the first time stellar kinematics was obtained for part of a shell. Agreement of stellar and gas velocities suggests that stars and gas in the shell are physically associated. C. Horellou, J. Black (Onsala), van Gorkom, F. Combes, J. van der Hulst (Groningen) and V. Charmandaris (Cornell) imaged the neutral hydrogen and molecular gas in the merger remnant and shell galaxy Fornax A. Very faint HI associated with the shells was found, while no HI is detected in the center. The presence or absence of HI in ellipticals that are obvious merger remnants deserves further study.

Chung, van Gorkom, K. O’Neil (NAIC) and G.

Bothun (Oregon) imaged in HI a sample of low surface brightness galaxies that were found to be strongly deviating from the Tully-Fisher relation from Arecibo observations. Analysis of the VLA data and a further analysis of the Arecibo sample shows that the Arecibo results were seriously affected by confusion. There is no evidence in the O’Neil sample for deviations from the Tully Fisher relation.

7 X-Ray Spectroscopy

Hailey along with Koglin, Jimenez-Garate, and graduate students Yu and Chonko, have been continuing work on the development of hard X-ray optics for both balloon-borne experiments and future satellite missions. The High Energy Focussing Telescope (HEFT) project is a hard X-ray detector for use between 20 and 100 keV. The optics are being built at Columbia. Several prototypes of the HEFT flight optic have been built in collaboration with Colorado Precision Products. Flight optics production will begin in November. HEFT is a collaboration between Columbia, CalTech, the Danish Space Research Institute and Lawrence Livermore National Laboratory. Fundamental research on improving the performance of thermally-slumped glass optics, invented by the Columbia-DSRI team continues, with an eventual goal of application on either the Constellation-X hard X-ray telescope or a small satellite.

Hailey is also collaborating with Mario Jimenez-Garate on analysis of high resolution spectroscopic data of Her X-1 taken with both Newton and Chandra. Hailey, along with graduate students Jaesub Hong and John Keck have continued work on compact X-ray sources observed with the γ -ray Arcminute Telescope Imaging System (GRATIS). A recent ApJ paper concerns multiwavelength observations of GRS 1758 and a confrontation of the observational data with predictions from advection dominated accretion flow theory. A paper has been submitted on 4U1700 and 1E1740.7 observations also made with GRATIS. Hong and Hailey are also working on the EXIST all-sky survey instrument design team.

Kinkhabwala, Sako, Behar, Paerels, and Kahn in collaboration with A.C. Brinkman, J.S. Kaastra, R. van der Meer (SRON), and D. A. Liedahl (LLNL) have performed detailed soft X-ray spectroscopy of the prototypical Seyfert 2 galaxy, NGC 1068, using data obtained from the Reflection Grating Spectrometer (RGS) on board the X-ray satellite *XMM-Newton*. The unique and powerful combination of high resolution and large effective area characteristic of the RGS allows for robust discrimination of different emission mechanisms. Emission lines from hydrogenic and heliumlike low-Z ions (from C to Si) and Fe L-shell ions dominate the spectrum. Of particular interest are the strong and narrow radiative recombination continua (RRC) for the C, N, O, and Ne ions, which imply that most of the observed soft X-ray emission arises in a low-temperature ($kT_e \sim 2 - 4$ eV) gas component. These RRC are produced by recombination in warm absorbing clouds photoionized by the inferred nuclear continuum, as expected in the unified

model of active galactic nuclei (AGN). They also find excess emission (compared with pure recombination) in all resonance lines ($1s \rightarrow np$) up to the photoelectric edge, providing definitive evidence for significant photoexcitation as well. To fit the spectrum, they employ a new, quantitative model of a cone of warm gas photoionized and photoexcited by the same power-law continuum. With this model, they find a remarkably good fit to each ionic line series by varying each ionic column density assuming global values for the velocity distribution and overall normalization (nuclear luminosity times covering factor). The ionic column densities we obtain are consistent with absorption seen in Seyfert 1 galaxies, providing a new, quantitative test of the unified model of AGN. Emission from a hotter, collisionally-ionized gas component in NGC 1068 is expected at some level given the evidence for circumnuclear starbursts at other wavelengths, however it makes an insignificant contribution in the soft X-ray band compared with that of the colder photoionized gas.

Kahn, Leutenegger, Cottam, and their collaborators G. Rauw and J.-M. Vreux (Université de Liège), A. J. F. den Boggende and R. Mewe (SRON), and M. Güdel (Paul Scherrer Institute) analyzed the first high resolution X-ray spectrum of the bright O4Ief supergiant star ζ Puppis, obtained with the Reflection Grating Spectrometer on-board *XMM-Newton*. The spectrum exhibits bright emission lines of hydrogen-like and helium-like ions of nitrogen, oxygen, neon, magnesium, and silicon, as well as neon-like ions of iron. The lines are all significantly resolved, with characteristic velocity widths of order $1000 - 1500 \text{ km s}^{-1}$. The nitrogen lines are especially strong, and indicate that the shocked gas in the wind is mixed with CNO-burned material, as has been previously inferred for the atmosphere of this star from ultraviolet spectra. They find that the forbidden to intercombination line ratios within the helium-like triplets are anomalously low for N VI, O VII, and Ne IX. While this is sometimes indicative of high electron density, they show that in this case, it is instead caused by the intense ultraviolet radiation field of the star. They use this interpretation to derive constraints on the location of the X-ray emitting shocks within the wind that are consistent with current theoretical models for this system.

Peterson and Paerels with their collaborators J. Kaastra (SRON), M. Arnaud (CEA/DSM/DAPNIA Saclay), T. H. Reiprich (Max-Planck-Institut für extraterrestrische Physik), A. C. Fabian (IOA, Cambridge), R. F. Mushotzky (NASA/GSFC), J. G. Jernigan (U.C. Berkeley), and I. Sakelliou (Mullard Space Science Laboratory) studied the soft X-ray spectrum of the massive cooling-flow cluster, Abell 1835. They presented detailed spatially-resolved spectroscopy results of the observation of Abell 1835 using the European Photon Imaging Cameras (EPIC) and the Reflection Grating Spectrometers (RGS) on the *XMM-Newton* observatory. Abell 1835 is a luminous ($10^{46} \text{ ergs s}^{-1}$), medium redshift ($z = 0.2523$), X-ray emitting cluster of galaxies. The observations supported the interpretation that large amounts of cool

gas are present in a multi-phase medium surrounded by a hot ($kT_e = 8.2 \text{ keV}$) outer envelope. They detected O VIII Ly α and two Fe XXIV complexes in the RGS spectrum. The emission measure of the cool gas below $kT_e = 2.7 \text{ keV}$ was much lower than expected from standard cooling-flow models, suggesting either a more complicated cooling process than simple isobaric radiative cooling or differential cold absorption of the cooler gas.

Haiguang Xu (Shanghai Jiao Tong University), Kahn, Peterson, Behar, and Paerels with collaborators R. F. Mushotzky (NASA/GSFC), J. G. Jernigan (U.C. Berkeley), and K. Makishima (University of Tokyo) presented the first high spectral resolution observation of the giant elliptical galaxy NGC 4636, obtained with the Reflection Grating Spectrometer on-board the *XMM-Newton* Observatory. The resulting spectrum contains a wealth of emission lines from various charge states of oxygen, neon, magnesium and iron. Examination of the cross-dispersion profiles of several of these lines provides clear, unambiguous evidence of resonance scattering by the highest oscillator strength lines, as well as the weak temperature gradient in the inner regions of the interstellar medium. They invoke a sophisticated Monte Carlo technique which allows them to properly account for these effects in performing quantitative fits to the spectrum. Their spectral fits are not subject to many of the systematics that have plagued earlier observations. The derived metal abundances are higher than have been inferred from prior, lower spectral resolution observations of this source, but are still incompatible with conventional models of elliptical galaxies. In addition, the data were incompatible with standard cooling flow models for this system – the derived upper limit to the mass deposition rate was below the predicted value by a factor of 3-5.

Peterson and Kahn with collaborator J. G. Jernigan (U.C. Berkeley) developed a number of new Monte Carlo methods for diffuse X-ray spectroscopy. They discuss the formulation of multivariate Monte Carlo methods in the context of spectroscopy of spatially-resolved X-ray sources. A number of optimization techniques have been employed to produce a highly efficient and flexible method for modeling extended X-ray sources in a variety of settings. χ^2 statistics on the projected data space and new multivariate versions of the Kolmogorov-Smirnov and Cramér-von Mises statistics were used to search the model parameter space.

Behar and Rasmussen, in collaboration with R.G. Griffiths (Leicester U.), K. Dennerl and B. Aschenbach (MPE), and A.C. Brinkman (SRON), obtained an observation of the supernova remnant N132D by the scientific instruments on board the *XMM* satellite. The X-rays from N132D are dispersed into a detailed line-rich spectrum using the Reflection Grating Spectrometers. Spectral lines of C, N, O, Ne, Mg, Si, S, and Fe are identified. Images of the remnant, in narrow wavelength bands, produced by the European Photon Imaging Cameras reveal a complex spatial structure of the ionic dis-

tribution. While K-shell Fe emission seems to originate near the centre, all of the other ions are observed along the shell. A high O^{6+} / O^{7+} emission ratio is detected on the northeastern edge of the remnant. This can be a sign of hot ionising conditions, or it can reflect relatively cool gas. Spectral fitting of the CCD spectrum suggests high temperatures in this region, but a detailed analysis of the atomic processes involved in producing the O^{6+} spectral lines leads to the conclusion that the intensities of these lines alone cannot provide a conclusive distinction between the two scenarios.

Behar, Sako, and Kahn have performed a full set of calculations for inner-shell $n = 2$ to 3 photoexcitation of the 16 iron charge states: Fe^{0+} (Fe I) through Fe^{15+} (Fe XVI). The blend of the numerous absorption lines arising from these excitations (mainly 2p - 3d) forms an unresolved transition array (UTA), which has been recently identified as a prominent feature between 16 - 17 Å in the soft X-ray spectra of active galactic nuclei (AGN). Despite the blending within charge states, the ample separation between the individual ion features enables precise diagnostics of the ionization range in the absorbing medium. Column density and turbulent velocity diagnostics are also possible, albeit to a lesser accuracy. An abbreviated set of atomic parameters useful for modeling the Fe 2p - 3d UTA is given. They show that the effects of accompanying photoexcitation to higher levels ($n \geq 4$), as well as the associated photoionization edges, may also be relevant to AGN spectra.

Sako and Kahn, in collaboration with G. Branduardi-Raymont and M.J. Page (MSSL), and A.C. Brinkman and J.S. Kaastra (SRON) have shown that XMM-Newton Reflection Grating Spectrometer (RGS) spectra of the Narrow Line Seyfert 1 galaxies MCG -6-30-15 and Mrk 766 are physically and spectroscopically inconsistent with standard models comprising a power-law continuum absorbed by either cold or ionized matter. They propose that the remarkably similar features detected in both objects in the 5-35 Angstrom band are H-like oxygen, nitrogen, and carbon emission lines, gravitationally redshifted and broadened by relativistic effects in the vicinity of a Kerr black hole. They discuss the implications of this interpretation, and demonstrate that the derived parameters can be physically self-consistent.

Sako, Kahn, and Behar, in collaboration with J.S. Kaastra and A.C. Brinkman (SRON), T. Boller (MPE), E. Puchnarewicz and R. Starling (MSSL), D.A. Liedahl (LLNL), and J. Clavel and M. Santos-Lleo (ESA) have observed the luminous infrared-loud quasar IRAS 13349 + 2438 with the XMM-Newton Observatory as part of the Performance Verification program. The spectrum obtained by the Reflection Grating Spectrometer (RGS) exhibits broad absorption lines from highly ionized elements including hydrogen- and helium-like carbon, nitrogen, oxygen, and neon, and several iron L-shell ions (FeXVII-XX). Also shown in the spectrum is the first astrophysical detection of a broad absorption feature identified as an unresolved transition array (UTA) of 2p-

3d inner-shell absorption by iron M-shell ions in a much cooler medium; a feature that might be misidentified as an OVII edge when observed with moderate resolution spectrometers. No absorption edges are clearly detected in the spectrum. They demonstrate that the RGS spectrum of IRAS 13349+2438 exhibits absorption lines from at least two distinct regions, one of which is tentatively associated with the medium that produces the optical/UV reddening.

Rasmussen, Behar, and Kahn, in collaboration with J.W. den Herder and K. van der Heyden (SRON) have presented the soft X-ray (5-35 Angstrom) spectrum of the supernova remnant (SNR) 1E 0102.2-7219 in the Small Magellanic Cloud, acquired by the reflection grating spectrometers (RGS) aboard ESA's XMM-Newton Observatory. Because the RGS features a large dispersion angle, spatial-spectral confusion is suppressed even for moderately extended sources. Consequently, these data, along with the spectrum of N132d (Behar et al. 2001), provide what are probably the most detailed soft X-ray spectrum of entire SNRs. The diagnostic power of performing spectroscopy using groups of emission lines from single ions is demonstrated. In particular, the bright Lyman and helium series lines for light elements (CVI, OVII, OVIII, NeIX & NeX) show peculiar ratios, where the values $[1s - np]/[1s - (n+1)p]$ are systematically weaker than expected for electron impact excitation close to ionization equilibrium, indicating nonequilibrium ionizing (NEI) conditions in the source. The well known temperature $G(T_e) = (i+f)/r$ diagnostics of helium-like triplets (OVII & NeIX) confirm this suggestion, with values that are inconsistent with ionization equilibrium. The temperatures implied are well above the maximum emission temperature T_m for each ion, and consistent with a purely ionizing plasma. The density diagnostics $R(n_e) = f/i$ meanwhile, are consistent with the low density limit, as expected.

Cottam and Kahn, in collaboration with A.C. Brinkman and J.W. den Herder (SRON), and C. Erd (ESA) have presented initial results from observations of the low-mass X-ray binary EXO 0748-67 with the Reflection Grating Spectrometer on board the XMM-Newton Observatory. The spectra exhibit discrete structure due to absorption and emission from ionized neon, oxygen, and nitrogen. They use the quantitative constraints imposed by the spectral features to develop an empirical model of the circumsource material. This consists of a thickened accretion disk with emission and absorption in the plasma orbiting high above the binary plane. This model presents challenges to current theories of accretion in X-ray binary systems.

Paerels and Mori, in collaboration with C. Motch (Strasbourg), F. Haberl and V.E. Zavlin (MPE), S. Zane, G. Ramsay, and M. Cropper (MSSL), and B. Brinkman (SRON) have presented the high resolution spectrum of the isolated neutron star RX J0720.4-3125, obtained with the Reflection Grating Spectrometer on XMM-Newton, complemented with the broad band spectrum observed with the EPIC PN camera. The

spectrum appears smooth, with no evidence for strong photospheric absorption or emission features. They briefly discuss the implications of the failure to detect structure in the spectrum.

Paerels and Rasmussen, in collaboration with H.W. Hartmann, J. Heise, A.C. Brinkman, C.P. de Vries, and J.W. den Herder (SRON) have presented the first high resolution photospheric X-ray spectrum of a Supersoft X-ray Source, the famous CAL 83 in the Large Magellanic Cloud. The spectrum was obtained with the Reflection Grating Spectrometer on XMM-Newton during the Calibration/Performance Verification phase of the observatory. The spectrum covers the range 20-40 Angstrom at an approximately constant resolution of 0.05 Angstrom, and shows very significant, intricate detail, that is very sensitive to the physical properties of the object. We present the results of an initial investigation of the spectrum, from which we draw the conclusion that the spectral structure is probably dominated by numerous absorption features due to transitions in the L-shells of the mid-Z elements and the M-shell of Fe, in addition to a few strong K-shell features due to CNO.

Li and Kahn, in collaboration with M.F. Gu (MIT) have derived a semianalytic solution for the structure of conduction-mediated transition layers above an X-ray-illuminated accretion disk, and calculated explicitly the X-ray line radiation resulting from both resonance-line scattering and radiative recombination in these layers. The vertical thermal structure of the illuminated disk is found to depend on the illuminating continuum: for a hard power-law continuum, there are two stable phases connected by a single transition layer, while for a softer continuum, there may exist three stable phases connected by two separate transition layers, with an intermediate stable layer in between. They show that the structure can be written as a function of the electron scattering optical depth through these layers, which leads to unique predictions of the equivalent width of the resulting line radiation from both recombination cascades and resonance-line scattering. We find that resonance-line scattering plays an important role, especially for the case in which there is no intermediate stable layer.

Cottam, Sako, Kahn, and Paerels, in collaboration with D.A. Liedahl (LLNL) have presented a preliminary analysis of the X-ray spectrum of the accretion disk corona source 4U 1822-37 obtained with the High-Energy Transmission Grating Spectrometer on board the Chandra X-Ray Observatory. They detect discrete emission lines from photoionized iron, silicon, magnesium, neon, and oxygen as well as a bright iron fluorescent line. Phase-resolved spectroscopy suggests that the recombination emission comes from an X-ray-illuminated bulge located at the predicted point of impact between the disk and the accretion stream. The fluorescent emission originates in an extended region on the disk that is illuminated by light scattered from the corona.

Kahn, in collaboration with B. Wargelin (SAO) and P. Beiersdorfer (LLNL) have observed $K\alpha$ spectra of

heliumlike neon and associated lithiumlike, berylliumlike, and boronlike satellite line emission with a high-resolution crystal spectrometer on the Lawrence Livermore Electron Beam Ion Trap. The KLL dielectronic recombination satellites were resolved from their He-like parent lines in electron energy space, and their wavelengths and resonance strengths measured. The wavelength measurements achieved a typical accuracy of a few Angstroms, with two measurements accurate to better than one part in 10000. By normalizing to the He-like resonance line, w, they measure Li-like satellite resonance strengths that are 10% to 46% lower than predicted by theoretical models. The wavelengths and relative strengths of Be-like KLL satellites were also measured, and absolute strengths were obtained by normalizing to the collisionally excited Li-like qr satellite blend.

8 Laboratory Astrophysics & Instrumentation

Aprile, Curioni, Giboni, Hussain, Kobayashi, Ni, Oberlack, Semple-Shuchter and Zhang, worked on the Liquid Xenon Gamma-Ray Imaging Telescope (LXe GRIT) project. The main activity in this period has been the Fall 2000 Balloon Flight Campaign in Ft. Sumner, NM and the subsequent analysis of the LXeGRIT calibration data taken before and after the flight, as well as the analysis of the flight data. Three students (Curioni, Hussain and Zhang) took part in the long flight campaign. On October 4, 2000, LXeGRIT was given the ok for a flight. A 28 Mcft helium filled balloon, carried the 2000-lb instrument afloat to a height of about 40 km. The flight was terminated in Buckeye, AZ, on October 5, 2000. For the entire flight period of 27 hours, including ascent, the LXeGRIT instrument and all its subsystems performed perfectly. The Crab and several other sources, e.g., 3C273 and Cygnus X-1, were in the large FOV (45 degrees). About 40 GB of data, of which about 80% was stored on-board, and the rest downlinked through two 500 kbps telemetry channels, were gathered. The total trigger rate remained constant around 700 Hz, after the expected increase during ascent. This rate includes about 400 Hz of charged particles, not vetoed during this flight. For the 2000 flight, the LXeGRIT time projection chamber was operated without any anticoincidence gamma or charged particle shield. The payload was recovered in almost perfect working condition and transported back to Columbia University Nevis Laboratory. Analysis and instrument tests and upgrades followed the flight. During the 2001 Summer, two new students got involved with LXeGRIT, Kaixuan Ni (a Physics graduate student) and Rachel Semple-Shuchter (a Barnard undergraduate student). They developed the software needed to study the Xe scintillation light collection efficiency in the detector, comparing the "old" PMTs system with the "new" one based on Hamamatsu R6041 PMTs, especially developed to work inside the liquid Xenon. Results from these calculations and ongoing laboratory measurements will guide the upgrade of the LXeTPC light readout system. Kaixuan Ni with Aprile, also measured the ionization re-

sponse to gamma rays in a 3 liter LXe chamber, and designed the changes for studies of simultaneous charge and light response with the new PMTs. Curioni, Husain, Kobayashi and Oberlack focused on the spectral and Compton imaging analysis of the preflight calibration and flight data. Much progress has been made on optimization of the complex event reconstruction and Compton sequence algorithms. We are completing the calibration data analysis, to finalize the instrument response function needed for imaging studies. At the same time, preliminary results from a quick search for a Crab signal in the flight data, were presented at the April Gamma2001 meeting. The analysis is being refined and exciting results are expected. More information on the LXeGRIT project, its publications, the instrument itself with pictures from the flight campaigns can be found at <http://www.astro.columbia.edu/~lxe/lxegrit> While the LXeGRIT data analysis and instrument upgrades continue, R&D on new detectors, from room temperature semiconductors (CdTe imaging array) to high pressure XeTPC (Aprile and Giboni), is also part of our activities towards the development of a next generation Advanced Compton Telescope for nuclear line and MeV continuum gamma-ray astrophysics.

Hailey and Mori, along with undergraduate Will Serber, have been studying a new technique for antimatter detection. The method involves stopping antimatter such as antiprotons in a very high pressure gas, and identifying the antimatter through the unique X-ray signature produced by the resultant antiatom. They have demonstrated this technique can provide an extremely sensitive means to search for dark matter. The antideuteron, which should be produced in neutralino annihilations, can be easily and unambiguously detected with this technique. This work has been accepted in ApJ (astro-ph/0109463). The work on this technique, called Gaseous Antiparticle Spectrometer (GAPS) was also done in conjunction with CalTech and Lawrence Livermore National Laboratory.

Savin has calculated the rate coefficients for $D(1s) + H^+ \rightleftharpoons D^+ + H(1s)$ using recently published theoretical cross sections. He presented results for temperatures T from 1 K to 2×10^5 K and provided fits to his data for use in plasma modeling. His calculations are in good agreement with previously published rate coefficients for $25 \leq T \leq 300$ K, which covers most of the limited range for which those results were given. His new rate coefficients for $T \gtrsim 100$ K are significantly larger than the values most commonly used for modeling the chemistry of the early universe and of molecular clouds. This may have important implications for the predicted HD abundance in these environments. Using his results, Savin has modeled the ionization balance in high redshift QSO absorbers. He finds that the new rate coefficients decrease the inferred D/H ratio by $\lesssim 0.4\%$. This is a factor of $\gtrsim 25$ smaller than the current $\gtrsim 10\%$ uncertainties in QSO absorber D/H measurements.

At the recent conference "Stellar Coronae in the *Chandra* and *XMM-Newton* Era," Savin and his col-

laborators Schippers, Böhm, and Müller (University of Giessen), and Gwinner, Schnell, Schwalm, and Wolf (Max Planck Inst. for Nuclear Physics) described the basic approach for measuring electron-ion recombination rate coefficients in merged-beams electron-ion collision experiments at heavy-ion storage rings. They presented an example of experimental results for the low temperature recombination of C IV ions and compared with the most recently recommended theoretical rate coefficient. The recommended value deviates by factors of up to 5 from the experimental value.

Savin, Behar, and Kahn and their collaborators Gwinner, Saghir, Schmitt, Grieser, Repnow, Schwalm, and Wolf (Max Planck Institute for Nuclear Physics), Bartsch, Müller, and Schippers (University of Giessen), Badnell (University of Strathclyde), Chen (LLNL), and Gorczyca (Western Michigan University) have measured the resonance strengths and energies for dielectronic recombination (DR) of Fe XX forming Fe XIX via $N = 2 \rightarrow N' = 2$ ($\Delta N = 0$) core excitations. They have also calculated the DR resonance strengths and energies using AUTOSTRUCTURE, HULLAC, MCDF, and R-matrix methods, four different state-of-the-art theoretical techniques. On average the theoretical resonance strengths agree to within $\lesssim 10\%$ with experiment. However, the 1σ standard deviation for the ratios of the theoretical-to-experimental resonance strengths is $\gtrsim 30\%$ which is significantly larger than the estimated relative experimental uncertainty of $\lesssim 10\%$. This suggests that similar errors exist in the calculated level populations and line emission spectrum of the recombined ion. Savin et al. confirm that theoretical methods based on inverse-photoionization calculations (e.g., undamped R-matrix methods) will severely overestimate the strength of the DR process unless the calculations include the effects of radiation damping. The team also finds that the coupling between the DR and radiative recombination (RR) channels is small. They have used our experimental and theoretical results to produce Maxwellian-averaged rate coefficients for $\Delta N = 0$ DR of Fe XX. For $kT \gtrsim 1$ eV, which includes the predicted formation temperatures for Fe XX in an optically thin, low-density photoionized plasma with cosmic abundances, the experimental and theoretical results are in good agreement. Savin et al. have also used their R-matrix results, topped off using AUTOSTRUCTURE for RR into $J \geq 25$ levels, to calculate the rate coefficient for RR of Fe XX. Their RR results are in good agreement with previously published calculations.

Using the electron beam ion trap EBIT-II facility at Lawrence Livermore National Laboratory, Gu, Kahn, Savin, and Behar and their collaborators Beiersdorfer, Brown, Liedahl, and Reed (Lawrence Livermore National Lab) have measured the iron L shell spectrum between 10.5 Å and 12.5 Å for Fe XXI – XXIV with spectral resolution of ~ 30 mÅ. The relative line intensities of strong 3→2 transitions for each charge state were measured as functions of electron energy and compared to distorted wave (DW) calculations. The contributions of

resonant processes, namely resonant excitation (RE) and spectroscopically unresolved dielectronic recombination (DR) satellites, were investigated. The RE contributions were shown to be less than the experimental and theoretical uncertainties for plasma in collisional ionization equilibrium. The unresolved DR satellites, however, enhance the emissivity of almost all lines, some by as large as 15%, consistent with the earlier measurements of Gu et al. for Fe XXIV. The DW results agree with their measurements to better than 20% under the condition of collisional ionization equilibrium. The line emissivities in the widely used spectral synthesis model, MEKAL, were also compared to our measurements and were found to be discrepant at $> 20\%$ level for some lines.

Savin and his collaborator Laming (Naval Research Laboratory) have investigated how the relative elemental abundances inferred from the solar upper atmosphere are affected by uncertainties in the dielectronic recombination (DR) rate coefficients used to analyze the spectra. They find that the inferred relative abundances can be up to a factor of ≈ 5 smaller or ≈ 1.6 times larger than those inferred using the currently recommended DR rate coefficients. They have also found a plausible set of variations to the DR rate coefficients which improve the inferred (and expected) isothermal nature of solar coronal observations at heights of $\gtrsim 50$ arcsec off the solar limb. Their results can be used to help prioritize the enormous amount of DR data needed for modeling solar and stellar upper atmospheres. Based on the work here, our list of needed rate coefficients for DR onto specific isoelectronic sequences reads, in decreasing order of importance, as follows: O-like, C-like, Be-like, N-like, B-like, F-like, Li-like, He-like, and Ne-like. Their work will help to motivate and prioritize future experimental and theoretical studies of DR.

Many of the fundamental questions in astrophysics can be addressed using spectroscopic observations of photoionized cosmic plasmas. However, the reliability of the inferred astrophysics depends on the accuracy of the underlying atomic data used to interpret the collected spectra. At the recent conference “Photoionized Plasmas 2000: The Challenge of High Resolution X-Ray through IR Spectroscopy of Photoionized Plasmas,” Savin reviewed some of the most glaring atomic data needs for better understanding photoionized plasmas.

Savin and his collaborators Ferland (University of Kentucky), Liedahl (Lawrence Livermore National Lab), Hamann (University of Florida), Kallman (NASA Goddard Space Flight Center), and Netzer (Tel Aviv University) co-organized the conference “Photoionized Plasmas 2000: The Challenge of High Resolution X-Ray through IR Spectroscopy of Photoionized Plasmas.” With the recent launches of *Chandra* and *XMM/Newton*, high resolution spectroscopy of photoionized plasmas at X-ray energies has become routine. HST and FUSE make the vacuum ultraviolet readily accessible. Ground-based optical telescopes can now obtain spectra of faint galaxies at the very edge of the visible Universe. And within a few years SOFIA and SIRTf will routinely provide high

resolution spectra in the mid- and far-infrared regions. Understanding the astrophysical messages contained in these spectra makes unprecedented demands on our understanding of atomic processes and our ability to simulate conditions in these non-equilibrium plasmas. The meeting brought together developers of plasma emission codes, experts in atomic physics and radiation transport, and the observers who are working to unravel the message in the spectrum. The main goals of the meeting were to identify current uncertainties, future needs, and promote research in quantitative spectroscopy. The conference proceedings were co-edited by Ferland and Savin.

Perhaps the greatest uncertainty remaining in our understanding of iron *L*-shell ions in collisionally-ionized cosmic plasmas is in the dielectronic recombination (DR) rate coefficients. At the recent conference “New Century in X-Ray Astronomy,” Savin and Kahn, and their collaborators Bartsch, Müller, and Schippers (University of Giessen), Chen (Lawrence Livermore National Lab), Grieser, Gwinner, Linkemann, Repnow, Saghiri, Schmitt, Schwalm, and Wolf (Max Planck Institute for Nuclear Physics), and Gorczyca (Western Michigan University), discussed the astrophysical importance of these rates and presented preliminary results for their recent measurements of DR onto Fe XIX.

High resolution X-ray spectra obtained by the *Chandra X-Ray Observatory* and the *X-Ray Multi-Mirror Mission* put new demands on atomic data including line positions, excitation cross sections, and radiative rates of cosmically-abundant highly-charged ions. To address these needs, Kahn, Savin, Gu, and Cottam and their collaborators Brown and Beiersdorfer (Lawrence Livermore National Lab), and Boyce, Gendreau, Gygax, Kelley, and Porter (NASA Goddard Space Flight Center) are performing measurements of the line emission from ions of cosmically abundant elements. The data are obtained at the Lawrence Livermore electron beam ion trap and work focuses on measurements of electron-impact excitation, dielectronic recombination, and resonance excitation as well as atomic structure measurements. We find that ratios of the electron-impact excitation cross section of singlet and triplet levels are systematically different from calculated values in the case of many highly charged ions. This, for example, has a profound impact on inferring optical depths from solar and stellar atmospheres. Moreover, new line identifications have been determined that resolve some long-standing puzzles in the interpretation of solar data. The importance of resonance contributions to spectral emission has also been assessed.

Savin and his collaborators Gwinner, Schwalm, and Wolf (Max Planck Institute for Nuclear Physics), Schippers and Müller (University of Giessen), Badnell (University of Strathclyde), and Gorczyca (Western Michigan University) are carrying out a combined experimental and theoretical program to study low-temperature dielectronic recombination (DR) in the iron *L*-shell ions Fe¹⁷ to Fe²³⁺. Measurements are being carried out using the TSR heavy-ion storage ring in Heidelberg, Germany.

L-shell iron ions play an important role in determining the line emission and thermal and ionization structure of cosmic photoionized plasmas. Successful modeling of these plasmas requires accurate ionization and recombination rate coefficients, particularly for low temperature DR which is the dominant recombination mechanism for most iron ions in photoionized plasmas. The dependence of DR on the detailed atomic structure makes it challenging to determine the needed DR rate coefficients theoretically, especially in many-electron systems. Their systematic survey of Li- to F-like Fe-ions is designed to produce high-resolution DR spectra which can be used to benchmark theory for ions of increasing complexity and to provide absolute low-temperature DR data required in astrophysics.

Paerels, Kahn, and Savin and their collaborators Brinkman, van der Meer, Kaastra, Kulkers, and den Boggende (SRON Laboratory for Space Research), Predehl (Utrecht University) and Drake and McLaughlin (Harvard-Smithsonian Center for Astrophysics) have found interstellar O K, Ne K, and Fe L absorption features in the the *Chandra X-Ray Observatory* Low-Energy Transmission Grating Spectrometer of the low-mass X-ray binary X0614+091. They have measured the column densities in O and Ne and find direct spectroscopic constraints on the chemical state of the interstellar O. These measurements probably probe a low-density line of sight through the Galaxy. The team members discuss the results in the context of our knowledge of the properties of interstellar matter in regions between the spiral arms of our Galaxy.

Savin, Kahn, and Behar and their collaborators Bannell (University of Strathclyde), Bartsch, Brandau, Hofknecht, Müller, and Schippers (University of Giessen), Chen (Lawrence Livermore National Lab), Gorczyca (Western Michigan University), Grieser, Gwinner, Linemann, Repnow, Saghiri, Schmitt, Schwalm, and Wolf (Max Planck Inst. for Nuclear Physics), and Závodszy (Michigan State University) have initiated a program of laboratory measurements and theoretical calculations to produce reliable low temperature dielectronic recombination rate coefficients for iron *L*-shell ions (Fe XVII to Fe XXIV). These ions play an important role in determining the line emission and thermal and ionization structures of photoionized gases. Existing uncertainties in the theoretical low temperature dielectronic recombination (DR) rate coefficients for these ions significantly affects our ability to model and interpret observations of photoionized plasmas. At the recent AIP Topical Conference “Atomic Processes in Plasmas” and the recent NASA workshop “Atomic Data Needs for X-Ray Astronomy,” Savin et al. presented some of their recent results and discussed some of the astrophysical implications.

At the recent NASA workshop “Atomic Data Needs for X-Ray Astronomy,” Kahn, Savin, and Gu and their collaborators Beiersdorfer, Brown, Chen, Lepson, and Utter (Lawrence Livermore National Lab) reported the recent strides they have taken to produce large sets of reliable data X-ray astronomy. Their work

includes measurements of ionization and recombination cross sections needed for charge balance calculations as well as the atomic data needed for interpreting X-ray line formations. These measurements were carried out using the Lawrence Livermore electron beam ion trap experiment, which is unique in its ability to provide direct laboratory access to spectral data under precisely controlled conditions that simulate those found in many astrophysical plasmas. This work is in support of X-ray observations by *Chandra*, *XMM-Newton*, *ASCA*, and *EUVE*.

Savin and his collaborators Träbert (University of Bochum), Beiersdorfer, Utter, Brown, and Chen (LLNL), Harris and Neill (University of Nevada at Reno), and Smith (Morehouse College) have measured transition probabilities of three magnetic dipole transitions in multiply charged ions of Ar. Electric dipole forbidden transitions between the fine-structure levels of ground configurations of ions are the origin of many solar coronal lines and are of great interest for plasma diagnostics. Measurements have been carried out using the Lawrence-Livermore electron-beam ion trap. Our results differ significantly from earlier measurements and are the most accurate ones to date

9 Other Theoretical Astrophysics

Chen and Spiegel [2001] have extended their work with Rao [Chen et al., 2001] on kinetic theory to the evaluation of the radiative bulk viscosity. Unlike what has been routinely done in previous studies, following the standard Chapman-Enskog procedure, they do not recycle earlier approximations through the current ones. The resulting expression for the bulk viscosity give values much larger than those obtained by earlier workers. Application of these results to dissipation in expanding media is currently being carried out. Another extension of this approach has been made to the case where the collision term is represented by the Fokker-Planck term. From this approximation, Spiegel and Jean-Luc Thiffeault of the Columbia Applied Physics Department have obtained macroscopic equations of motion for use in plasmas and stellar systems; a paper, which is in preparation, is to be published in a festschrift for D.O. Gough.

Thieberger (Ben Gurion University) and Spiegel have studied the influence of projection effects on the dimensions of fractal distributions of points. The purpose of this is to be enable the estimation of the dimensions of distribution of objects from two-dimensional sky catalogues (Thieberger and Spiegel, 2001).

With the group of A. Provenzale, Spiegel has studied the statistical output of a discrete model of on/off intermittency, a mechanism which produces bursty behavior. The aim of this work has been to show how this mechanism is a route to chaos, that its statistical output exhibits scaling behavior and is very like that seen in models of self-organized criticality (Toniolo, et al., 2002).

Pasquero, Provenzale and Spiegel have computed the enhanced rate of the broadening of the spectrum

of droplet sizes in rain clouds under the influence of turbulence [Pasquero, et al., 2001]. The aim is to apply their approach to the related problem of the growth of particles in the early solar nebula.

Kinney has been involved in two primary research projects in the past year. The first, in collaboration with Brian Greene and Richard Easther at Columbia, and Gary Shiu at Penn, concerns studying the effect of very short distance physics on the cosmological perturbations generated during inflation. The second, in collaboration with Martina Brisudova and Richard Woodard from University of Florida, Gainesville, concerns the development of cosmological models incorporating a long-range repulsive force.

Y. Li started to work with Mac Low on the propagation of ionization fronts in turbulent gas. She applied the ionization code by Tom Abel (Harvard CFA) to the turbulent molecular cloud simulated with ZEUS code by Mac Low. An analytic model based on the average clumping factor was able to reproduce the numerical results.

Yecko and Zaleski (Paris VI) have completed work on the basic shear instability that is present at the interface of two sheared immiscible fluids. The possibility of strong Tollmein-Schlichting type unstable modes (in addition to the well known Kelvin Helmholtz mode) at large Reynolds numbers was found, and is a new result for problems of this type (a paper was submitted 10/2001). Direct numerical simulations of this problem have also revealed two distinct scaling regimes in the ultimate breakup of the surface, suggesting that multiple modes are relevant to long time development of the instability.

Windt is performing research directed at the development of multilayer X-ray optics for astronomy and solar physics. A new instrument for observing the solar corona, using narrow-band, normal-incidence multilayer mirrors in a novel geometry, was developed with L. Golub (SAO), and launched successfully on a sounding rocket in June, 2001. The instrument allows for high-resolution photometric imaging at wavelengths tunable contouously over the range 17.1 – 21.1 nm. Significant progress has been made over the past year to extend this approach of ultra-high-resolution, normal-incidence X-ray imaging to previously unresolved galactic and extra-galactic sources as well. In particular, new multilayer coatings have been developed that operate at wavelengths as short as 2-3 nm, where absorption by the interstellar medium can be avoided. These coatings, when deposited onto recently developed aspherical mirror substrates with 0.1-0.2 nm figure and finish, can be used to construct diffraction-limited X-ray telescopes having sub-milliarsecond resolution, in order to resolve stellar coronae, interacting binaries, globular clusters, and AGN. Finally, progress has been made in the development of depth-graded multilayer coatings designed for broad-band reflectance at grazing incidence, at X-ray energies above 10 keV. These coatings are currently being deposited onto thermally-formed glass shells

to construct highly-nested Wolter telescope modules for a balloon instrument (HEFT), in collaboration with F. Harrison (Caltech), C. Hailey, W. Craig (LLNL), and F. Christensen (DSRI), that is expected to be launched in 2002. This instrument will provide sub-arcminute resolution up to 70 keV, for observations of AGN and young SNR. New multilayer coatings, designed for use at energies up to 200 keV, are also being investigated, and prototype structures containing 1100 periods with layer thickness below 1 nm are currently under test.

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