# Columbia University
# Department of Astronomy/Department of Physics

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This report covers the period September 2002 through August 2003 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, Andrei Beloborodv, Arlin Crotts, Karl-Ludwig Giboni, Eric Gotthelf, Charles Hailey, Zoltan Haiman, Jules Halpern, David Helfand, Lam Hui, Steven Kahn, Laura Kay (Barnard), Amber Miller, 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 Schwarz, Philip Yecko and Catharine Garmany. Norman Baker retired in July 2003. New faculty appointments include David Schiminovich and Janna Levin (Barnard).

Graduate students participating in research were Antara Basu-Zych, Douglas Bramel, Tzu-Ching Chang, Aeree Chung, James Chonko, Alessandro Curioni, Mark Dijkstra, Akimi Fujita, Suvi Gezari, Eilat Glikman, Mark Jackson, Miranda Jackson, Benjamin Johnson, Moo Kwang (Ryan) Joung, Ali Kinkhabwala, Maurice Leutenegger, Yuexing Li, Adam Lidz, Andrei Mesinger, Nestor Mirabal, Kaya Mori, Anthony Mroczkowski, Stephen Muchovej, James Don Neill, Kaixuan Ni, John Peterson, Andreea Petric, Pietro Reviglio, Jacob Noel-Storr, David Spiegel, Ben Sugerman, Shen Wang, Haitao Yu, Michel Zamojski. Undergraduates participating in research were Anne Abramson, Eve Armstrong, Ibrahima Bah (Lafayette), Randy Berkowitz, Tiffany Christatos (Barnard), Maya Cohen (Barnard), Benjamin Collins, Alexander Cosmas (Columbia Engineering), Catherine Espaillat, Regina Flores (Barnard), Amy Goldman (Barnard), Rebecca Grossman (Barnard), Karina Hamalainen (Barnard), Susan Hu, Paul Jawlik (Biosphere), David Krohn, Floris Lugt (visiting from Kapteyn Institute, Groningen), Sharlissa Moore (Biosphere), Marcia Sanders (Barnard), Rachel Semple Schuchter (Barnard), Samuel Singer (Biosphere), Dana Stern (Barnard), Jin Suh, T.T. Tao, Gisela Telis, and Pauline Wang (Barnard). Research staff assistants include Alex Bergier, Alan Gersch, Mala Mateen and Adam Fallon.

Tzu-Ching Chang, Akimi Fujita, Ali Kinkhabwala, Ben Sugerman and John Peterson received Ph.D. degrees.

Appointments during 2002–2003 were held by Adjunct Professors Michael Allison from the Goddard Institute for Space Studies, and Michael Shara and Mordecai MacLow from the American Museum of Natural History. Postdoctoral Research Scientists appointments were held by David Alves, Marc Audard, Edward Baltz, Martin Bureau, Fernando Camilo, Soizik Donguy, Jason Koglin, Richard Easther, Masanori Kobayashi, William Kinney, Stephen Lawrence, Patrick Cseresnjes, Caleb Scharf and Jacob Vink. Paul Vanden Bout (NRAO) and Deepto Chakrabarty (MIT) were visiting research scientists.

Helfand continued as Chair of the Astronomy Department, Paerels continued as Director of the Columbia Astrophysics Laboratory, Weinberg continued as Chair of the Physics Department, and Kay continued as Chair of the Physics and Astronomy Department at Barnard. Halpern continued as Director of the MDM Observatory.

## 1. STARS AND STELLAR EVOLUTION

The Center for Backyard Astrophysics accumulated ~800 nights of observation during 2002-3. 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 observations 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 Uzbekistan, Canada, Utah, and Connecticut. Most programs involve the study of cataclysmic variables, justly famous for the many periods present in their light curves.

Through the study of ‘‘superhumps’’ in the light curves of dwarf novae, we succeeded in measuring accretion-disk precession rates in ~30 new stars, and calibrated a scheme for measuring mass ratios from those rates. We also obtained a tight constraint of the mass-radius relation of the secondary stars in cataclysmics. The secondaries have an average radius of $18\pm6\%$ greater than the radius of a theoretical ZAMS star. This small expansion may be due to the star's mass loss on a timescale close to its thermal timescale.

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

Leutenegger, Kahn and collaborators D. Cohen, R. Kramer, and J. Reed (Swarthmore), and S. Owocki (Delaware) are studying the profiles of emission lines in the *Chandra* HETGS and *XMM-Newton* RGS X-ray spectra of O-type stars. A simple empirical model is used to fit the profiles. The profile shapes are found to be generally consistent with emission from shocks distributed throughout the stellar wind. However, the characteristic optical depths inferred are systematically too small by about an order of magnitude. This result poses problems for our understanding of X-ray emission from hot stars.

Paerels and student researcher Telis reduced the X-ray spectroscopy of the LMC Supersoft X-ray Source CAL 83. A high signal-to-noise spectrum obtained with the *XMM-*

*Newton* RGS exists, which shows intricate, and probably only partially resolved, absorption structure. The spectrum is complemented by a deep exposure with the *Chandra* LETGS, which covers the band out to the long wavelength ISM absorption cutoff. Both spectra agree perfectly in the area of overlap around the carbon K edge; the increased bandwidth will increase the diagnostic leverage. Quantitative interpretation, to be pursued based on dedicated model atmosphere calculations, will yield an estimate for the luminosity and mass accretion rate of the white dwarf, and establish whether this type of binary is a viable candidate progenitor for Ia supernovae.

Paerels, Kahn, M. Sako (Stanford), and collaborators at ISAS in Japan, interpreted the Compton recoil spectrum first identified in the Fe K$\alpha$ fluorescent emission of the massive binary GX301-2, as observed in the high resolution *Chandra* HETGS spectrum of the source. The detailed shape of the feature probes the conditions in the Compton-thick gas surrounding the fluorescent source. A detailed treatment of the scattering with a dedicated Monte Carlo simulation indicates that the entire sky, as seen from the photon source, is filled with cold scattering electrons. The effects of a finite electron temperature, and of multiple Compton scattering, are clearly detected. High resolution X-ray spectroscopy has therefore now also given us a quantitative probe of the dense, near-neutral gas in the stellar wind, which is otherwise only observable in the heavily saturated resonance absorption lines in the UV.

Audard and collaborators from the *XMM-Newton* RGS consortium studied the coronal abundances in several RS CVn binaries observed by *XMM-Newton*. The Reflection Grating Spectrometer and European Photon Imaging Camera spectra were fitted simultaneously with several collisional models. Audard and colleagues found that coronal abundances in the most active binaries show a marked pattern correlated with the First Ionization Potential; contrary to the solar FIP effect, the coronal abundances increase with increasing FIP. However, stars with intermediate activity, such as Capella, show no correlation with the FIP. The authors showed that their results fit well with the transition observed in solar analogs in which the least active stars display a solar-like FIP effect whereas the most active show an inverse FIP effect.

Audard collaborated with M. Güdel (Paul Scherrer Institut), and other colleagues to study the coronal X-ray emission of the binary $\alpha$ Coronae Borealis. While the secondary (a young solar analog) is a typical coronal star, the primary (an A-type star) is not magnetically active and thus is X-ray dark. *XMM-Newton* obtained a deep light curve of the secondary eclipse thanks to its sensitive EPIC cameras. Güdel, Audard, and collaborators constructed two-dimensional maps of the X-ray brightness on and around $\alpha$ CrB B using iterative eclipse mapping reconstruction codes. The maps reveal similar distribution of X-ray bright regions and large areas with little flux, showing the inhomogeneity of the corona of the young solar analog.

Audard, M. Güdel (Paul Scherrer Institut), and S. Skinner (Univ. of Colorado) studied the X-ray emission of the nearby flare star UV Ceti. For the first time *Chandra* was able to separate X-rays from each component of this detached binary. Audard and colleagues found that, despite their similar spectral types (dM5.5e), their X-ray activity differ drastically: the B component showed enhanced magnetic activity, displaying several large flares and even a huge, short flare with a peak luminosity a hundred times the low-level X-ray emission. On the other hand, UV Cet A showed weak modulation; however, its low-level flux was similar to UV Cet B. Numerous radio observations of the UV Ceti binary system have also shown that the coronae of the two components differ significantly. While the differences remain unexplained, they could be related to the magnetospheric configurations. UV Cet B is indeed spatially resolved in the radio.

Audard, J.-U. Ness (Hamburger Sternwarte), and colleagues have systematically investigated the opacity effects and coronal densities in stellar coronae. Line ratios of some Fe Ne-like lines are sensitive to optical depth. The observed ratios in a large sample of coronal stars displaying a wide range of magnetic activity showed no evidence for opacity effects, implying that the spatially unresolved X-ray emission of magnetically active stars is in average optically thin. Coronal densities on the other hand showed a different picture: low densities were measured in all active RS CVn binaries and relatively higher densities (but still below $10^{11}$ $cm^{-3}$) for all other active stars.

Audard, M. Güdel (Paul Scherrer Institut), and colleagues studied the nearest star, Proxima Centauri, observed simultaneously in X-rays and in the U band by *XMM-Newton*. They found strongly variable X-ray coronal emission, with flares ranging over a factor of a hundred in peak luminosity. Several X-ray flares are preceded by an optical burst, as predicted by standard solar flare models. A very large X-ray flare displayed significant variations in density across several phases of the flare. However, abundance ratios showed little variability. The flare light curve was modeled with an analytic flare model, with the finding that the flaring loop system should have large characteristic sizes of the order of a stellar radius.

Audard, A.J.J. Raassen (SRON), and colleagues investigated the X-ray spectrum of the flare star AT Microscopii observed by *XMM-Newton*. Its coronal emission measure distribution ranged from about 1 to 60 MK. Coronal abundances seem to follow the inverse FIP effect; during a flare the abundance of low-FIP elements increased slightly, as often observed in other active stars. Contrary to the similar flare star AU Mic (see below), the density in AT Mic did not vary during the flare.

Audard, E. van de Besselaar (SRON), and colleagues investigated the X-ray emission of the flare star AD Leonis observed by *XMM-Newton* and *Chandra*. AD Leo displayed several flares that were studied in detail. In particular the emission measure distribution during non-flaring times was compared to the flaring emission measure distribution, showing an increase of high-temperature plasma in the flare state. Coronal abundances did not show a clear correlation with the FIP, although a weak inverse FIP effect was suggested. An increase of the electron density during flares was suggested from the grating spectra, although the uncertainties remained large.

Audard presented a review of stellar coronae observed with *XMM-Newton* at the biannual general assembly of the Committee for Space Research in Houston, TX. At the same meeting, Audard, H. Magee (MSSL), and colleagues showed preliminary results of the electron density measured in the He-like O VII triplet increased from the low-density limit in average periods to higher values during flares.

Audard and several colleagues studied the very hot corona of the fast rotating giant YY Mensae. The *Chandra* and *XMM-Newton* grating spectra show a strong continuum, several Fe lines at high ionization states, and lines from mostly H-like transitions, implying a very hot coronal temperature in YY Men. The temperature is so high that line broadening, interpreted as Doppler thermal broadening, could be detected in several lines. YY Men displayed a high N abundance and a strong C depletion, reflecting the CN cycle in the stellar interior. The authors also showed preliminary results of the *Chandra* grating observation of V824 Ara, a young RS CVn binary. The plasma temperature is cooler than in YY Men; the coronal abundances showed a marked inverse FIP effect as often found in active binaries.

Audard, K. Briggs (Paul Scherrer Institut), and colleagues studied the pre-main sequence stars in the Orion star-forming complex with *XMM-Newton*. More than a hundred PMS stars were detected. The authors observed no correlation between X-ray activity proxies and rotation proxies. However, these results cannot exclude a solar-like dynamo because these stars appear in the saturated regime. Audard, Briggs, and colleagues showed that low-mass stars with strong blue excesses tend to have lower X-ray luminosities, suggesting that accretion suppresses magnetic activity.

Audard, A. Telleschi (Paul Scherrer Institut), and colleagues investigated the coronal emission of a sample of solar analogs spanning a wide range of age and magnetic activity. They obtained the emission measure distributions from different approaches and compared the derived distributions, which turned out to be very similar. The younger stars showed more emission measure at high temperatures. The coronal abundances showed a transition from a solar-like FIP effect in rather inactive stars to an inverse FIP effect in the most active analogs.

Undergraduate student Suh and Audard studied the X-ray emission of the bright RS CVn binary $\sigma^2$ Coronae Borealis observed by *XMM-Newton*. The coronal abundances in this X-ray bright binary showed no correlation with the first ionization potential. Since most active RS CVn binaries show an inverse FIP effect, the absence of pattern in $\sigma^2$ CrB remains unexplained. Maybe it is related to the fact that it is composed of two similar main-sequence stars (which is atypical of RS CVn binaries). Suh and Audard reported a low upper limit for the electron density.

Kinkhabwala, Peterson, Kahn, and Paerels collaborated with K. Mukai (GSFC) on analysis of seven X-ray spectra of cataclysmic variables. They found that their spectra divide unambiguously into two distinct types. Spectra of the first type are remarkably well fitted by a simple cooling flow model, which assumes only steady-state isobaric radiative cooling. The maximum temperature and the normalization, which provides a highly precise measurement of the accretion rate, are the only free parameters of this model. Spectra of the second type are grossly inconsistent with a cooling flow model. They instead exhibit a hard continuum and show strong H-like and He-like ion emission but little Fe L-shell emission, which is consistent with expectations for line emission from a photoionized plasma. Using a simple photoionization model, they argue that the observed line emission for these sources can be driven entirely by the hard continuum. The physical significance of these two distinct types of X-ray spectra, in particular the lack of correspondence of these spectral types with classifications based on other wavelengths, is also explored.

Yecko and undergraduates A. Cosmas (Columbia Engineering) analyzed data obtained at the Biosphere 2 Observatory for candidate delta Scuti variables to serve as complements to an ongoing theoretical study of the delta Scuti instability strip. The star SAO 83225 was found to be misidentified by the ROTSE project as a delta Scuti variable; the nearby star GSC 2007:761 however, is found to be an apparent eclipsing variable, previously unknown, of period 0.26 days.

## 2. $\gamma$-RAY SOURCES

Establishing the nature of the majority of the high-energy $\gamma$-ray sources discovered by the EGRET instrument on *CGRO* is a problem that requires an intensive multiwavelength observational effort. The Columbia group continues to obtain new observations with *Chandra* and *XMM* that will be used to search for periodicities in promising pulsar candidates within EGRET error circles. In the coming year we expect to receive such data on the radio quiet neutron star tentatively identified with 3EG J1835+5918, the brightest unidentified EGRET source at high Galactic latitude, as well as on a pulsar wind nebula associated with 3EG J1809–2328. Whether $\gamma$-ray sources are associated with star-forming regions is also being investigated. Mukerjee *et al.* are studying X-ray sources in the field of TeV J2032+4130, the first unidentified TeV source discovered by HEGRA.

The MDM Observatory continues to pursue optical observations of afterglows of $\gamma$-ray bursts (GRBs) under the direction of Halpern and Mirabal. The event rate has increased with the successful operation of the HETE–2 satellite. Several GRB locations were observed in 2002–2003. MDM photometry obtained by Bureau contributed to a detailed study by Y.M. Lipkin (Tel Aviv U.) *et al.* (in preparation) of the afterglow of the nearby ($z = 0.1685$) GRB 030329 and its associated supernova light curve. Images and light curves of successful observations of GRBs at MDM Observatory are maintained at *http://www.astro.columbia.edu/grouprsearch.html*. Mirabal and Halpern will investigate whether a bright X-ray afterglow of ‘‘dark’’ GRB 970815 was observed by *ASCA* and *ROSAT* by making a follow-up observation with *Chandra*.

## 3. PULSARS, NEUTRON STARS, & SUPERNOVAE

Camilo, Gotthelf, Halpern, and Helfand, along with their students and collaborators, continue to identify neutron stars and study their pulsar wind nebulae in supernova remnants (SNRs) using the combination of X-ray imaging with *Chan-*

*dra*, and sensitive pulsar searches with large single-dish radio telescopes (Arecibo, GBT, Parkes, Jodrell Bank). Current targets of interest include CTA1 and CTB 87. A detailed X-ray and radio study of an energetic pulsar previously found using these techniques, PSR J2229+6114, is in preparation. Camilo and collaborators also continue to extract results from the completed Parkes multibeam pulsar survey, as well as to make detailed studies of old, millisecond pulsars in globular clusters.

Gotthelf and Halpern are studying the newly discovered anomalous X-ray pulsar XTE J1810–197, having used *Chandra* and *XMM* to localize the source and measure its pulsations and spectrum. AXPs are young neutron stars whose radiation is apparently not powered by rotation or accretion, but rather by the decay of superstrong magnetic fields (the magnetar model). XTE J1810–197 is important because it is the second example of a transient AXP, which increased in flux by two orders of magnitude from its quiescent level as an inconspicuous *ROSAT* and *ASCA* source. The discovery that AXPs can spend most of their time in an inactive state may connect them with the soft gamma-ray repeaters (SGRs) and other faint X-ray sources in SNRs that are even less well understood. They may represent a new channel for the birth of neutron stars at a rate that has been significantly underestimated.

Paerels, with collaborators L. Bildsten and P. Chang (UC Santa Barbara), investigated the implications of the measured line strengths of the proposed photospheric absorption lines discovered in the X-ray burst spectrum of the neutron star in EXO0748-676. A classical curve of growth analysis indicates that the observed equivalent widths are too large by a large factor to be accounted for by thermal Doppler broadening alone. A simple parameterized treatment of the expected Stark broadening of the lines shows that the line equivalent widths are in the right regime to be explicitly sensitive to the broadening mechanism, and this makes the line spectrum sensitive to the acceleration of gravity at the stellar surface. The implications of these findings will be worked out quantitatively, resulting in the first measurement of the mass and the radius of a single neutron star.

Bildsten, Chang, and Paerels also studied the details of the accretion of metals onto the neutron star (gas is nearly in free fall if the measured gravitational redshift at the stellar surface of $z = 0.35$ is correct), raising the interesting possibility of observing rare spallation products in sensitive X-ray spectroscopy. This issue is now being pursued with a large allocation of observing time with the *Chandra* observatory.

Hailey and Chonko are collaborating with K. Mori at the Canadian Institute for Theoretical Astrophysics on neutron star spectroscopy. They are continuing their work on the neutron star 1E1207.4, which is unique in showing several absorption features in its spectrum.

## 4. ACTIVE GALACTIC NUCLEI

Gezari, 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 and LINERs. An explanation of this association in terms of the ion torus (or advection-dominated accretion flow) continues to be attractive. The profiles of these double-peaked lines are highly variable on timescales 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, in particular, one-armed spirals. A comparison study of the ultraviolet emission lines of some of these objects is underway with *HST*.

Halpern and Gezari, together with S. Komossa (MPE) are continuing to investigate the few candidate tidal disruption events that were discovered by *ROSAT* in otherwise non-active galaxy nuclei. Follow-up X-ray observations will continue to be made to test for the predicted decline of the accretion rate in the fall-back phase after the tidal disruption of a star by a supermassive black hole.

Kinkhabwala, Behar, Sako, Kahn, Paerels, collaborated with Gu on creation of a detailed model of the discrete X-ray spectroscopic features expected from steady-state, low-density photoionized plasmas. They apply the Flexible Atomic Code (FAC) to calculate all of the necessary atomic data for the full range of ions relevant for the X-ray regime. These calculations have been incorporated into a simple model of a cone of ions irradiated by a point source located at its tip (now available as a suite of codes for use with the widely-used X-ray spectral analysis software XSPEC). For each ionic species in the cone, photoionization is balanced by recombination and ensuing radiative cascades, and photoexcitation of resonance transitions is balanced by radiative decay. This simple model is useful for diagnosing X-ray emission mechanisms, determining photoionization/photoexcitation/recombination rates, fitting temperatures and ionic emission measures, and probing geometrical properties (covering factor/column densities/radial filling factor/velocity distributions) of absorbing/reemitting regions in photoionized plasmas. Such plasmas have already been observed in diverse astrophysical X-ray sources, including active galactic nuclei, X-ray binaries, cataclysmic variables, and stellar winds of early-type stars, and may also provide a significant contribution to the X-ray spectra of gamma-ray-burst afterglows and the intergalactic medium.

Using the suite of X-ray analysis software described above, Kinkhabwala, Kahn, and Peterson collaborated with Gu on analysis of an X-ray spectrum of the Seyfert 1 galaxy MCG –6-30-15. They perform a variability analysis of its complex X-ray spectrum using recent observations with the *XMM* PN and RGS. Its variable spectrum is remarkably consistent at high spectral resolution with a simple model of a component with varying normalization (but no change in spectral shape) plus a constant component. The variable component is well fit by a power-law with (non-variable) ionic absorption from ions spanning a large range in ionization. The constant component exhibits a hard power-law-like spectrum with near-neutral Fe K$\alpha$ emission line and near-neutral Fe K edge (both consistent with reflection by distant Compton-thick material) plus a softer, emission-line-rich component (explained, at least in part, as line reemission from the ionic absorber)!

Notably, their model for MCG –6-30-15 *does not* require the following: (1) a soft excess due to a disk blackbody or relativistically-broadened C, N, or O Ly$\alpha$ lines, (2) a relativistically-broadened Fe K$\alpha$ line, or (3) dust absorption. Ionic absorption in MCG is similar to ionic absorption in the Seyfert 1 galaxy NGC 3783. Also, the observed constant line reemission is consistent with the inferred level of absorption. The constant component overall is somewhat reminiscent of the spectra of typical Seyfert 2 galaxies, such as NGC 1068, for which line reemission in the ionic absorber plus a hard reflection component (including Fe K$\alpha$ and an Fe K edge) are also observed, providing tentative evidence for a particularly simple X-ray version of the unified model of active galactic nuclei.

## 5. SURVEYS

Chang and Helfand, in collaboration with A. Refregier (Saclay), have successfully completed their search for gravitational weak lensing shear in the FIRST radio survey data. They measure the shear correlation functions on angular scales of $0.5° - 40°$, and compute the corresponding aperture mass statistics. On scales $1° - 4°$, they detect a lensing E-mode signal significant at the $3.8\sigma$ level. After removing nearby radio sources with optical counterparts, the *E*-mode signal increases by about 20-30%, as expected for a lensing signal derived from more distant sources. They use this measurement to constrain the mass power spectrum normalization $\sigma_8$ and the median redshift $z_m$ of the unidentified radio sources. They find $\sigma_8(z_m/1.5)^{0.6} \simeq 0.99 \pm 0.26$ where the $1\sigma$ error bars include statistical errors, cosmic variance, and systematics. This is consistent with earlier determinations of $\sigma_8$ from cosmic shear, the cosmic microwave background (CMB) and cluster abundance, and with current knowledge of the redshift distribution of radio sources. Taking the prior $\sigma_8 = 0.9 \pm 0.1$ (68%CL) from the WMAP experiment, this corresponds to $z_m = 1.8^{+0.9}_{-0.6}$ (68%CL) for radio sources without optical counterparts, consistent with existing models for the radio luminosity function of radio sources. These results offer promising prospects for precision measurements of cosmic shear with future radio interferometers such as LOFAR and SKA.

Helfand, with Caltech collaborators F. Harrison, M. Eckart, and D. Stern, have completed photometric and spectroscopic observations of a sample of over 1000 hard X-ray sources serendipitously detected in 27 *Chandra* fields. This SEXSI survey increases by a factor $\sim 5$ the total number of hard X-ray-selected sources known in the flux range where the $logN - logS$ relation changes slope, and from which the bulk of the X-ray background arises. Papers on the X-ray catalog and optical photometry have been completed; current work centers on analyzing the more than 500 redshifts and spectroscopic classifications derived from Keck spectroscopy of the sample. Significant constraints on models for the origin and evolution of the XRB-contributing populations should follow.

Helfand with collaborators R. White (STSCI), R. Becker (UC Davis) and others completed work on a deep *I*-band-selected quasar sample. Remarkably, they find that the five most luminous quasars with $z < 1.3$ in a 16 deg$^2$ region are *all* extremely reddened objects, lending support to the notion that there is a substantial population of highly obscured quasars missed by all existing optical surveys. They are followng up this result with spectroscopic observations of deeper samples selected in the *I* band, both with and without FIRST radio source counterparts. In related work, Glikman, along with collaborators M. Gregg (LLNL) and M. Lacy (IPAC) and the foregoing authors, are collecting samples of reddened quasars among candidates drawn from matching the 2MASS catalog to the FIRST survey. They have found that the criteria $R - K > 4.0, J - K > 1.7$ define a region in color-color space where more than 50% of the objects are obscured quasars. Over 75 such objects have been spectroscopically identified to date. In order to better define the reddening law appropriate to these objects, they are collecting data on low-*z* quasars in order to construct a high signal-to-noise template of quasar spectra in the near-IR band.

Helfand and Fallon, along with collaborators Becker and White continue their Galactic plane survey work. Low-resolution data now cover the longitude region from 5° to 32°; high-resoluton data for the lower-longitude half of the survey will be obtained in the coming year. A catalog of over 1000 radio sources to a flux density threshold of 1-2 mJy has been compiled from the $19° < \ell < 32°$ region. In addition, Helfand and collaborators R. Warwick, M. Watson, and A. Hand (all from Leicester U.), have compiled a catalog from a three-degree region of the survey covered by their X-ray Galactic Plane Survey program with *XMM-Newton*; over 400 point sources and dozens of diffuse sources are cataloged. Indeed, the two known supernova remnants *and* the four brightest HII regions are all detected as diffuse hard X-ray sources. Followup observations with *XMM* and the *Chandra* Observatory are in progress, and further X-ray survey work at lower longitudes is scheduled.

Bureau and the SAURON team, a collaboration with a core of twelve members, continued operation of the panoramic integral-field spectrograph SAURON, mounted on the William Herschel Telescope (WHT). The team completed a large representative survey of nearby early-type galaxies, producing two-dimensional maps of the stellar kinematics, ionized-gas distribution and kinematics, and absorption line-strength indices. The data are currently being published and will subsequently be made public. A pipeline called PALANTIR has also been completed, allowing the automatic (re)reduction of data in an automated fashion.

Work is in progress to determine the intrinsic shape of the sample galaxies, model the stellar kinematics, and constrain the age and metallicity of the stellar populations, ultimately shedding light on the connection between gas, stars, and the chemical enrichment history of the systems. Bureau in particular is leading an effort to quantify the presence of central stellar disks in spheroids, and to characterize their structure. Bureau is also leading an effort to obtain complementary ground-based optical imaging of all galaxies using the MDM Observatory 1.3m telescope. Similarly, the SAURON Team has obtained complementary high spatial resolution integral-field spectroscopy of half the sample using OASIS on the Canada-France-Hawaii Telescope (CFHT), in an effort to better constrain the structure, kinematics, and stellar populations of the very inner parts of the objects. Reduction and analysis of the data is ongoing, and spectacular examples of decoupled kinematics have already been uncovered. Follow-up SAURON surveys of later type bulges, late-type disks, and large barred galaxies have also begun and are in the data taking stages.

Neill and Shara used the Calypso Telescope to survey M81 for novae in H$\alpha$ for 5 continuous months. They observed 12 novae during this period and derived a nova rate of $39^{+15}_{-9}$ novae yr$^{-1}$ from Monte Carlo simulations using frame limits for each epoch and a set of complete nova H$\alpha$ light curves. This represents the most accurate nova rate for any galaxy to date. Using the 2MASS Large Galaxy Atlas to normalize the nova rate to the underlying K-band stellar luminosity gives a luminosity specific nova rate (LSNR) of $\rho_k = 4.68^{+1.8}_{-1.1}$ yr$^{-1}[10^{10}L_{\odot,K}]^{-1}$. This is more than double the previous value reported in the literature and implies a significant systematic underestimate of the LSNR published for most other galaxies due to missing novae close to the centers of galaxies. Indeed, the novae discovered by Neill and Shara in M81 are preferentially found in the bulge where many nova surveys suffer their largest incompleteness. Neill and Shara plan to continue producing accurate nova rates for nearby galaxies with the goal of detecting a relationship between LSNR and host galaxy Hubble type or age of the underlying stellar population.

## 6. GALAXIES & CLUSTERS OF GALAXIES

Sugerman (in collaboration with Crotts and an international team from Cerro Tololo Inter-american Observatory, Carnegie Observatories and Hofstra University) has reconstructed, via light echoes, the three-dimensional structure of the nebula surrounding Supernova 1987A (the closest observed supernova in over three centuries) to provide the first detailed information about the complete mass-loss envelope from a star that later went supernova. This nebula extends over more than 10 pc and includes many structures, including some recently discovered by Sugerman (and in the past by Crotts and other investigators), and represents the first such structure studied in such detail for such a massive star (or indeed nearly any star). In addition, Sugerman (and Crotts, along with another international team from several universities and institutions) has found several new features arising along the innermost prominent edge of this nebula as the ejecta from the supernova explosion begins to rip the nebula apart to form a supernova remnant. These discoveries are included in Sugerman's recently completed Ph.D. work.

A team at Columbia (Alves, Baltz, Bergier, Cseresnjes, Gersch, led by Crotts, in collaboration with an international team from Kapteyn Institute, MSSSO, U. of Chicago, Queens U. and Cambridge U.) have found the first of what are probably a large collection of gravitational microlensing event candidates from a survey of most of the stars in M31. The distibution of the positions of these events across the face of M31 is suggestive of a large contribution from lenses in the halo of the galaxy, tending to confirm still controversial results from our own Galaxy by other research groups. The presence of such objects in M31 is also consistent with an earlier study just completed at Columbia (by Uglesich, Crotts, Baltz and several investigators from the larger team above as well as the Vatican Observatory).

Scharf with collaborators in the US and the UK discovered the most distant known diffuse X-ray emitting object – a cloud of intense X-rays surrounding a massive galaxy forming some 1.5 billion years after the Big Bang. A supermassive black hole in the center of this system is ejecting electrons at close to the speed of light; the electrons are then scattering far infra-red photons from the cosmic microwave background and from warm dusty regions in the galaxy up to X-ray energies. Scharf's observations, made with NASA's *Chandra* Observatory, further indicate that this X-ray emission is likely influencing the physical state of the primordial gas falling into this young galaxy, which may help to relieve a major problem whereby current cosmological models predict too many massive galaxies in the Universe. In a follow-on study, Scharf and collaborators have also discovered that this system is likely the birthplace of a cluster of galaxies, and find a remarkable ''nest'' of massive black holes in neighboring objects, which is an expected, but previously unconfirmed marker of merging proto-galaxies.

Scharf, Bureau, and D. Zurek (AMNH) used the NASA *Chandra* X-ray Observatory for a total of 140 hours to map out the Fornax cluster of galaxies - one of the two closest such systems at only 60 million light years distance. Owing to its relative proximity they are able to resolve details at an unprecedented level. The data show galaxies falling into the cluster with ''cometary'' X-ray emission as their gas haloes are distorted in the hotter gas halo of the cluster, and a remarkable population of stellar X-ray sources associated with star clusters and possibly extra-galactic star systems within the cluster. This survey represents the most detailed X-ray map of a galaxy cluster ever made.

To probe the origin of the numerous central stellar disks uncovered at the center of spheroids by SAURON, Bureau is part of an effort to probe the molecular content of the SAURON galaxies, together with van Gorkom, L. Young (New Mexico Tech), and F. Combes (Observatoire de Paris). A single-dish CO survey with IRAM is about half-completed and interferometric follow-up observations are being acquired with BIMA, with three galaxies observed so far. Ground-based broadband observations of all elliptical galaxies ever searched for CO are also being acquired with the National Optical Astronomy Observatory (NOAO) 2.1m telescope, in an effort to find correlations between the presence of molecular gas in spheroids and morphological substructures.

Following similar work using periodic orbit calculations and hydrodynamical simulations, Bureau and E. Athanassoula (Observatoire de Marseille) have completed work to develop kinematic bar diagnostics in edge-on disks using N-body simulations. This is necessary because bars in edge-on spirals can not be identified reliably using morphological arguments alone. Contrasting with an axisymmetric disk, the most important features are a double-peaked rotation curve, a rather flat velocity dispersion peak with secondary maxima, and a Gauss-Hermite $h_3$ profile correlating with $V$. The latter appears to be a telltale signature of triaxiality.

Chung and Bureau used the N-body diagnostics to study the stellar kinematics of a large sample of boxy and peanut-shaped (B/PS) bulges, present in about 45% of all edge-on spirals. Bar signatures were identified in most of the galaxies, which show rotation curves with a double-hump feature and a dip or plateau and velocity dispersion profiles either peaked or flat at the center, with secondary peaks present where $V$ flattens out. The asymmetric parameter $h_3$ correlates with $V$ in what appears to be the barred regions of the galaxies, as expected for non-axisymmetric disks. Unlike the expectations from simulations, however, $h_3$ shows a strong anti-correlation with $V$ in the very center of most early-type galaxies. This indicates that these galaxies probably contain inner stellar disks, most likely formed from gas accumulated at the center of the bars, and not taken into account by the N-body simulations. Chung and Bureau concluded that most spirals with a B/PS bulge are the edge-on projection of a thick bar, as suggested by simulations, and that the skewness of the velocity profiles ($h_3$) is indeed a useful tracer of asymmetries in disks.

Together with G. Aronica (Ruhr-Universitat Bochum) and E. Athanassoula (Observatoire de Marseille), Bureau continued a study of the vertical structure of bars using K-band imaging of the same sample of boxy and peanut-shaped bulges studied with Chung. First results are just about to be published; unsharp-masking reveals embedded rings and truncated outer disks, confirming that the bulges are bars seen edge-on. In addition, unsharp-masking enhances substructures within the bulges, revealing the shape of the orbits reaching to large galatic heights, and confirming predictions from simple three-dimensional bar models. Preliminary fits to the vertical light distribution also show that the disk scale-heights and the shapes of the (vertical) light profiles vary considerably with radius, supporting formation through bar buckling. More detailed comparisons with N-body simulations are ongoing.

Zamojski and Bureau are currently working on a project to study stellar kinematics as a function of galactic height in (barred) spiral galaxy bulges. Spectra at various heights above the equatorial plane have been obtained for a subsample of the galaxies studied by Chung and Bureau, the main goal being to verify if the galaxies are rotating cylindrically (i.e. independently of height), as predicted by N-body simulations. This is crucial for constraining theories of galaxy formation, particularly the importance of bar-driven secular evolution along the Hubble sequence.

With J. Falcon-Barroso (Leiden University) and other members of the SAURON Team, Bureau carried out a detailed analysis of the S0 galaxy NGC7332, where existing ground-based and HST photometry reveal a double disk structure and a boxy (presumably barred) bulge. The SAURON two-dimensional stellar kinematic maps confirmed the existence of the bar and inner disk but also uncovered the presence of a cold counter-rotating stellar component within the central 250 pc. The $H\beta$ and [OIII] emission line maps show that the ionized gas has a complex morphology and kinematics, including both a component counter-rotating with respect to the stars and a fainter co-rotating one. The absorption line-strength maps spectacularly show that NGC7332 is young everywhere. The presence of a large-scale bar can explain most of those properties, but the fact that we see a significant amount of unsettled gas, together with a few peculiar features in the maps, suggest that NGC7332 is still evolving. Interactions as well as bar-driven processes must thus have played an important role in the formation and evolution of NGC7332, and presumably of S0 galaxies in general.

With T. Kouwenhoven (Leiden Observatory), and as part of an effort to enlarge the number of well-studied Magellanic dwarf irregular galaxies, Bureau analyzed broadband optical imaging and low-resolution HI interferometric observations of the dwarf galaxy ESO364-029. The optical morphology characteristically shows a bar-like main body with a one-sided spiral arm, an approximately exponential light distribution, and offset photometric and kinematic centers. The HI is mildly asymmetric and, although slightly offset from it, loosely follows the optical light, extending to over 1.3 Holmberg radii. In particular, the highest HI column densities and velocity dispersions closely follow the bar and one-arm spiral. The rotation is solid-body in the inner parts but flattens outside of the optical extent. Higher resolution but shallow HI observations suggest a very complex small-scale HI structure, with evidence of numerous shells and holes, but deeper observations are required for a quantitative study and a proper comparison with the Large Magellanic Cloud (where, despite an optical morphology similar to ESO364-029, the HI bears little resemblance to the optical).

Together with F. Walter (NRAO), van Gorkom, and C. Carignan (Universite de Montreal), Bureau is leading an HI survey of the outskirts of the nearby M81 group of galaxies using the Very large Array (VLA). The survey encompasses the star forming dwarf galaxies M81dwA and UGC4483, as well as HoII, where evidence of ram pressure stripping by an as yet undetected intergalactic medium was recently discovered. The survey has now been completed and analysis is ongoing. Preliminary results show no evidence of large-scale tidal debris and no free-floating HI. The morphology of the HI in the outer parts of HoII is however much better constrained than before, and two lopsided arm-like structures are observed. These are consistent with being tidal features, having a morphology characteristic of that expected from interactions, but they could also be consistent with ram pressure stripping, due to rotationally-aided stripping and compression-driven annealing, as recent models with cooling show. The case for an intergalactic medium in the M81 group is thus still open, but the survey puts the strongest constraints to date on possible counterparts to the local high velocity clouds (HVCs) in an external group, reaching a 3-sigma column density of about $10^{19}$ cm$^{-2}$.

Van Gorkom continues her work on gas and galaxy evolution and its environmental dependence. She is working on an ongoing VLA HI survey of clusters in the local universe with H. Bravo-Alfaro (Guanajuato), Dwarakanath (NRAO &

RRI, Bangalore), P. Guhathakurta (UCSC), B. Poggianti (Padova), D. Schiminovich (Caltech), M. Valluri (Chicago), M. Verheijen (Potsdam), E. Wilcots (Wisconsin) and A. Zabludoff (Arizona). This survey is aimed at probing statistically the evolution of galaxies as they move from the low density outer parts to the dense inner parts of the clusters. Six clusters have been imaged so far. The HI detection rate varies enormously from cluster to cluster with, as a most probable cause, the dynamical state of the ICM. An analysis of the star formation rate in A2670 by Lugt (Kapteyn Institute) strengthens this conclusion – the merger of subclumps seem to enhance the SFR.

J. Kenney (Yale University), Vollmer (Univ. of Strassbourg) and van Gorkom have been allocated VLA survey time for a new HI survey of selected galaxies in the Virgo cluster. This survey will be ten times more sensitive than previous surveys and is aimed at studying in detail the processes that affect galaxy evolution in a cluster environment. The data will be used to constrain hydrodynamical simulations of galaxy evolution in clusters. The first galaxy observed as part of this survey, NGC 4522, displays all the characteristics of an ongoing ICM-ISM interaction, yet the simple scenarios to explain the observations don't work. The estimated ram pressure based on ROSAT images give a pressure that is too low by almost an order of magnitude. Quite possibly, also here, cluster-subcluster merging enhances the effect of the ICM on the ISM.

Chung, with van Gorkom, K. O'Neil (NAIC) and G. Bothun (Univ. of Oregon) are working on a survey for new LSB galaxies as part of her thesis on the nature of low surface brightness galaxies.

Chung, M. Verheijen, M. Yun (U. Mass), and Y. Rhee (Korea) have analyzed a CO survey on galaxies in the Ursa major cluster.

Noel-Storr and van Gorkom with S. Baum, C. O'Dea, G. Verdoes-Klein (all STSci) and Carollo (ETH, Zurich) are analyzing STIS data of a representative sample of nearby radio galaxies. The goal is to derive the masses of the black holes and determine the physical conditions of the gas surrounding the black hole.

Rasmussen, Kahn and Paerels detected nondirectional OVII line absorption toward X-ray bright BL Lac objects using long integration time exposures of the RGS aboard *XMM-Newton* Observatory. Correspondingly, the presence of a hot ($T_e \sim 300$ eV), tenuous ($n_e < 2 \times 10^{-4}$) and extended ($L > 140$ kpc), Local Group medium was inferred. To place constraints on a nearby contribution to this absorption, Rasmussen has acquired and analyzed a very high quality ISM absorption spectrum toward Scorpius X-1, which in itself is novel. Absorption signatures for several ionization states of Oxygen are clearly seen in that spectrum. To place better constraints on the nature of the Local Group medium absorption, Rasmussen is attempting to improve the available data quality, by using the public *XMM* Science Archive for better sky coverage, and by improving methods for combining multiple data sets. One eventual goal is to provide better constraints on the velocity distribution for the OVII absorption feature, which will address the origin of the hot Local Group medium.

## 7. LARGE SCALE STRUCTURE AND COSMOLOGY

Haiman has been investigating the beginning of structure formation in the Universe. Together with student Dijkstra, M. Rees (Cambridge) and D. Weinberg (Ohio State) they revisited the suppression by a UV background of gas infall into low–mass dark halos. They found that, in contrast to previous results obtained at low redshifts, in the early universe ($z \gtrsim 10$), the UV background does not prohibit gas cooling infall even in halos with velocity dispersions as small as $v \sim 10$ km/s. In a related study, however, Haiman and P. Oh (Caltech) found that the earliest light sources are much more effective than previously believed in prohibiting gas cooling and infall in even smaller ($v < 10$ km/s) halos. After such sources turn off, the ionized gas recombines and cools. Nevertheless, this gas remains on a high adiabat, which prevents it from contracting to high densities. These findings are highly relevant to the interpretation of the recent discovery by the *Wilkinson Microwave Anisotropy Probe (WMAP)* of a large electron scattering optical depth, making this discovery much more puzzling than it naively appears. Haiman & G. Holder (IAS, Princeton) studied detailed models of the reionization history of the universe that included various feedback processes. A particular challenge at the present time is for such models to simultaneously account for the *WMAP* result, which suggests that reionization started as early as $z \sim 20$, and the Gunn-Peterson troughs seen in the spectra of distant quasars, which suggests reionization is ending as late as $z \sim 6$. Haiman and Hui have shown that additional evidence for the latter statement comes from the thermal history of the intergalactic gas. S. Hansen (Zurich) and Haiman proposed a possible alternative explanation, where reionization at high redshift is caused by a decaying sterile neutrino, rather than by stars or quasars, as conventionally believed. Together with L. Knox, M. Kaplinghat, M. Santos (UC Davis), G. Holder (IAS, Princeton) and A. Cooray (Caltech), Haiman also studied the important question of how to distinguish competing reionization models in future datasets. Several methods seem to be promising, such as studying the spectra and abundance of distant Ly$\alpha$-emitting galaxies, or using future measurements of the polarization and temperature anisotropies in the cosmic microwave background (CMB) on small and large angular scales. Finally, together with D. Spergel and E. Turner (Princeton), Haiman considered the direct detection of distant galaxies in mid–infrared wavebands, and made predictions for the number density of such galaxies using semi–analytic models.

Haiman and collaborators also investigated several aspects of the formation and evolution of supermassive black holes. Haiman, L. Ciotti (Bologna) and J. Ostriker (Cambridge) studied the simple hypothesis that quasar black holes and the spheroids of galaxies grow in mass over cosmic timescales at a rate proportional to one another, and found this hypothesis to be consistent with existing observations. Haiman also contributed to the interpretation by X. Fan (Arizona) *et al.* of the discoveries of bright quasars at $z \sim 6$, suggesting the presence of supermassive $M \sim 10^9 M_\odot$ black holes at these redshifts. The growth of such massive black holes in the short cosmic time available prior to $z \sim 6$ is a challenge to models. Together with J. Comerford (Princeton) and J. Schaye (IAS, Princeton), Haiman showed that gravitational lensing could frequently cause strong amplification of the flux of these sources (due to selection effects), which would ease this challenge, in principle. However, Haiman and R. Cen (Princeton) subsequently showed that strong lensing is unlikely to occur for at least one of the $z\sim6$ quasars. This source is surrounded by a very large (30 comoving Mpc) local ionized zone, suggesting that it is intrinsically very bright indeed.

Haiman and collaborators also continued investigating the usefulness of a large (future) sample of galaxy clusters to constrain the amount and nature of dark matter and dark energy. Together with collaborator W. Hu (Chicago), Haiman found that tight and robust, purely geometric constraints can be available from the statistics of the spatial distribution of clusters in a large solid–angle survey. Together with S. Molnar (Rutgers), M. Birkinshaw (Bristol, UK) and R. Mushotzky (Goddard Space Flight Center), Haiman showed that systematic errors (e.g., in determinations of cluster masses) can be controlled efficiently by combining Sunyaev-Zeldovich decrement and X–ray data for a sample of a few hundred clusters, along with the redshift distribution of these clusters.

Lidz, Hui and Crotts, along with A. Zaldarriaga (Harvard) have completed a study of the ‘‘Alcock-Paczyński effect’’ which is an excellent indicator of the strength of the cosmological constant or ‘‘dark energy’’ term that seems to be causing runaway expansion of the Universe. Their results indicate (at a somewhat statistically marginal level) that the cosmological constant exists (close to the level required for the expansion effect). Lidz *et al.* improve techniques which will be useful in a larger survey that may be able to much better define the amount of dark energy in the Universe. Such a survey is underway, involving efforts at Columbia.

Miller and collaborators from Berkeley, MSFC, and the University of Chicago reported results from a continuing study of small-scale anisotropy in the CMB using the BIMA Array. The survey consists of ten fields selected for low infrared dust emission and a lack of bright radio point sources. Modeling the observed power spectrum with a single flat band power with average multipole of $\ell_{eff}=68643$, we find $dT=14.2^{+4.8}_{-6.0}\mu K$ at 68% confidence. The signal in the visibility data exceeds the expected contribution from instrumental noise with 96.5% confidence. We have also divided the data into two bins corresponding to different spatial resolutions in the power spectrum. We find $dT_1=16.6^{+5.3}_{-5.9}\mu K$ at 68% confidence for CMB flat band power described by an average multipole of $\ell_{eff}=5237$ and $dT_2<26.5\mu K$ at 95% confidence for $\ell_{eff}=8748$.

Miller and collaborators from the University of Chicago, MSFC, Hawaii, Berkeley, Durham, and NAS observed eight galaxy clusters from the MACS survey confirming that they are hot, massive clusters. From SZE data alone, X-ray temperatures and masses were derived. X-ray derived masses and temperatures exist for only two of these clusters and are found to be in good agreement with the SZE-derived values from this work.

## 8. OTHER THEORETICAL ASTROPHYSICS

Ruderman has been considering answers to the the question ‘‘What is being learned about isolated neutron stars from *Chandra* and *XMM* observations of their soft X-ray emission?.’’ (1) A very young neutron star is expected to be immersed in a continually replenished electron-positron plasma whose cyclotron-resonance scattering of soft X-rays interferes with direct observation of the stellar surface. Consequences of this appear to agree well with X-ray observations. (2) Among the six reported millisecond pulsars whose low energy X-ray emission have been observed, five appear to be orthogonal rotators and one an aligned one. This distribution and other properties, especially of PSR 0437, have been shown to agree well with those expected from spin-up of a superfluid/superconducting neutron star. (3) Mori and Ruderman have reconsidered spin-down of magnetars and the transition from carrying away spin-angular momentum by a stellar wind to the propeller-effect interaction between a magnetar’s spinning magnetosphere and the surrounding medium. Application has been made to modelling the observed X-ray emission from J1856.

C. Toniolo (Nice), A. Provenzale (Turin) and Spiegel continued their study of the nature of on/off intermittency, a mechanism for bursting behavior that they believe is central to the intermittency of the solar cycle as well as other bursty astrophysical processes. Behind the on/off systems there lie dynamical processes with one or more unstable invariant manifolds near which the systems may hover, displaying quiescent behavior before going off in an unstable direction to execute bursting activity. Systems driven by the on/off mechanism may exhibit the same kind of scaling attributed to SOC and can produce 1/f noise. An analysis of this process has been published in PRE.

The coagulation of rain droplets and small particles is influenced by the motions of the ambient fluid. C. Pasquero (Cal Tech), A. Provenzale (Savona) and Spiegel have studied the influence of ambient turbulence on the size distribution of small droplets. They analyze the ability of the turbulence to keep particles suspended for long times and show how this may affect the distribution of particle sizes. The work has been described in PRL.

In continuation of the work previously reported, J.-L. Thiffeault (Imperial College) and Spiegel have explored the continuum equations that result when the kinetic theory is based on the Fokker-Planck mechanism. The resulting continuum equations have been presented in a volume dedicated to D.O. Gough’s sixtieth birthday.

A. Parodi (Savona), J. v. Hardenberg (Savona), G. Passoni (Milan), A. Provenzale and Spiegel have been studying the aggregation of small convective structures into large structures on the scale of the full system. The work is based on accurate three-dimensional simulations of the Boussinesq equations of plane parallel convection at Rayleigh numbers around $10^7$. The results show how thermals gather together into large clusters and the peak of the turbulent energy spectrum moves to ever larger horizontal wave numbers until the limit of the computational domain is reached. A report on the results has been submitted for publication.

Yecko has calculated transient growth factors and optimal modes for a sheared liquid-gas interface with variable density and viscosity contrasts and boundary layer profiles. This configuration is relevant to Kelvin-Helmholtz instabilities and, apart from the presence of surface tension, applies to mixing in white dwarf stars, stellar winds and stellar and galactic jets. The fully three-dimensional calculations show strong transient growth in the form of streamwise-oriented vortices with little or no streamwise variability. The structure of the optimal modes suggests their possible role in forming often-seen ligament patterns in unstable jets. Stronger density contrasts enhance transient growth factors. A spin-off of this work focused on the planar jet was begun in collaboration with Drs. C. Dumouchel and J. Cousin (both CORIA/CNRS, Univ. Rouen, France) and Dr. H. Nuglisch (Siemens VDO, Toulouse, France).

Yecko extended earlier work on the behavior of three-dimensional disturbances in rotating boundary layers of the Blasius and asymptotic suction form, flows relevant to accretion disks. New results show that cross-flow effects lead to more unstable transient growth in Blasius flow, contrasting the stabilizing effect of cross-flow on modal stability. Another new results shows the form of optimal modes morph continuously from streamwise vortices for weak rotation to spanwise two-dimensional vortices for strong rotation.

One of the most common constituents of meteorites are small glassy beads known as chondrules. They are known to have formed within a few million years after the Sun, probably before most of the planets. Their glassy nature can only be reproduced by heating followed by cooling over several hours, much longer than their cooling time in free space. No completely satisfactory model for this heating has yet been found. Joung and Mac Low worked with Ebel (AMNH) on a new model relying on current sheets produced in partially ionized gas to do the heating that may address many of the problems.

Most models of the collapse of molecular clouds into star clusters have assumed an isothermal equation of state that generally reproduces the observations of local star formation. However, varying abundances or radiation environments may change the effective equation of state. Li worked with R. Klessen (Astron. Inst. Potsdam) and Mac Low to model how changing the adiabatic index changes the fragmentation properties. They found that raising the index to 1.3-1.4 suppresses fragmentation, while lowering it below unity strongly enhances fragmentation.

Star formation in primordial galaxies will have strong effects on the surrounding intergalactic gas, perhaps preventing it from collapsing into galaxies by heating from ionization or turbulence. Fujita completed her thesis with Mac Low on this topic. They studied the fraction of ionizing radiation escaping from these galaxies in collaboration with C. Martin (UC Santa Barbara) and T. Abel (Penn State), and fraction of mass and kinetic energy escaping in the blowout of supernova-driven winds with A. Ferrara (SISSA) and A. Meiksin (Edinburgh).

## 9. LABORATORY ASTROPHYSICS

Savin and his collaborators T. Gorczyca, C. Kodituwakku, K. Korista, and O. Zatsarinny (Western Michigan University), N. Badnell (University of Strathclyde), E. Behar (Technion University), and E. McGuire (Lawrence Livermore National Laboratory) have investigated the accuracy of the 1s vacancy fluorescence database of Kaastra & Mewe resulting from the initial atomic physics calculations and the subsequent scaling along isoelectronic sequences. In particular, they have focused on the relatively simple Be- and F-like 1s vacancy sequences. They find that the earlier atomic physics calculations for the oscillator strengths and autoionization rates of singly charged B II and Ne II are in sufficient agreement with our present calculations. However, the substantial charge dependence of these quantities along each isoelectronic sequence, the incorrect configuration averaging used for B II, and the neglect of spin-orbit effects (which become important at high Z) all cast doubt on the reliability of the Kaastra & Mewe data for application to plasma modeling.

Savin and Kahn and their collaborators G. Gwinner, M. Grieser, R. Repnow, G. Saathoff, D. Schwalm, and A. Wolf (Max Planck Institute for Nuclear Physics), A. Müller and S. Schippers (University of Giessen), O. Závodszky (Michigan State University), M.H. Chen (Lawrence Livermore National Laboratory), T. Gorczyca and O. Zatsarinny (Western Michigan University), and M.F. Gu (MIT) have measured dielectronic recombination (DR) resonance strengths and energies for carbonlike Fe XXI forming Fe XX and for boronlike Fe XXII forming Fe XXI via $N=2\rightarrow N'=2$ core excitations. All measurements were carried out using the heavy-ion Test Storage Ring at the Max Planck Institute for Nuclear Physics in Heidelberg, Germany. They have also calculated these resonance strengths and energies using three independent, state-of-the-art perturbative techniques: a multiconfiguration Breit-Pauli (MCBP) method using the code AUTOSTRUCTURE, a multiconfiguration Dirac-Fock (MCDF) method, and a relativistic configuration interaction method using the Flexible Atomic Code (FAC). Overall reasonable agreement is found between their experimental results and their theoretical calculations. The most notable discrepancies tend to occur for relative collision energies $\lesssim 3$ eV. They have used the measured $2\rightarrow 2$ results to produce Maxwellian-averaged rate coefficients for Fe XXI and Fe XXII. Their experimentally-derived rate coefficients are estimated to be accurate to better than $\approx 20\%$ both for Fe XXI at $k_BT_e > 0.5$ eV and for Fe XXII at $k_BT_e > 0.001$ eV. For these results, they provide fits which are accurate to better than 0.5% for Fe XXII at $0.001 \leqslant k_BT_e \leqslant 10000$ eV and for Fe XXII at $0.02 \lesssim k_BT_e \leqslant 10000$ eV. Their fitted rate coefficients are suitable for ionization balance calculations involving Fe XXI and Fe XXII in photoionized plasmas. Previous published Burgess formula and LS-coupling calculations are in poor agreement with their experimentally-derived rate coefficients. None of these published calculations reliably reproduce the magnitude or temperature dependence of their experimental results. Their previously published Fe XXI MCDF results are in good agreement with their experimental results for $k_BT_e \gtrsim 0.07$ eV. For both ions in this temperature range their new MCBP, MCDF, and FAC results are in excellent agreement with their experimentally-derived rate coefficient.

Mroczkowski and Savin and their collaborators R. Rejoub, P. Krstić, and C. Havener (Oak Ridge National Laboratory) have used a merged-beams technique, to measure the absolute, total electron-capture cross section for collisions of $Ne^{2+}$ ions with hydrogen (deuterium) atoms at collision energies between 139 and 1489 eV/u. The data are compared to three published measurements, two of which differ from one another by a factor greater than two. Early quantal rate coefficient calculations for $Ne^{2+}$ ions with hydrogen at eV/u energies indicate a cross section many orders of magnitude below the previously measured cross section at 40 eV/u. A possible explanation is given for the discrepancy between theory and experiment. These new data will help to improve Ne abundance determinations from planetary nebulae.

## 10. TELESCOPES AND INSTRUMENTATION

Construction has been completed and first light achieved on a 6-meter diameter optical telescope with an innovative ‘‘liquid mirror’’ exploiting the concept of ‘‘newton’s bucket’’ to inexpensively produce an accurate paraboloidal figure. Researchers at Columbia (Johnson, Crotts, Helfand), along with those from U. British Columbia and State U. of New York, Stony Brook, have recently brought this telescope into operation and designed a scientific program which will intensively monitor a 30 square-degree strip of sky for variable objects such as distant supernovae (mostly type Ia), and find photometric redshifts for many objects such as distant galaxies.

Miller, Muchovej, and Mroczkowski worked on the Sunyaev-Zel’dovich Effect Array (SZA). This new interferometric array of telescopes is a collaboration between Miller’s group at Columbia, Carlstrom’s group at the University of Chicago, Joy’s group at MSFC, and members of the Owens Valley Radio Observatory. The goal of this project is to detect and image the Sunyaev-Zel’dovich Effect in clusters of galaxies in frequency bands centered at 30 GHz and 90 GHz with a bandwidth of 8 GHz. We plan to survey 12 square degrees of sky detecting all clusters with masses larger than $\sim 10^{14} h^{-1}$ solar masses, providing a mass-limited sample of clusters. We will use this sample along with follow-up optical observations to measure the growth rate of structure in the universe. In addition to the survey, we will conduct follow-up observations with the SZA at higher resolution in order to produce detailed images of the SZE in galaxy clusters. In combination with X-ray and optical observations and cluster simulations, Miller, Muchovej, and Mroczkowski plan to collaborate with Paerels, Haiman, and Scharf to study the internal structure of these objects.

Major progress towards the deployment of the SZA has taken place at Columbia this year. We have completed and debugged the full prototype receiver. The first production SZA reciever also constructed in the lab currently meets all rf and cryogenic requirements for implementation on an SZA telescope. We are currently building and testing the remaining eight receivers (for eight telescopes and one spare). Integration with the telescopes currently being assembled in Chicago and on site in the Owens Valley will begin in November of this year and first light is expected in January 2004.

Miller and collaborators from Goddard, NIST, Princeton, Penn, Harvard, Case Western, University of Chicago, Rutgers, Toronto, and UCLA, formed a group to study the feasibility of building a CMB polarization satellite designed to detect the B-mode signature of primordial gravity waves. A proposal for this project called CMBpol was submitted to NASA.

Aprile, Curioni, and Kobayashi (who left in March 2003) worked on the Liquid Xenon Gamma-Ray Imaging Telescope (LXeGRIT) project. The analysis of data gathered during the Fall 2000 Balloon Flight Campaign has been completed. The two main goals of this analysis were 1) a detailed study of the background measured at balloon altitude and 2) imaging studies of the Crab Nebula in the MeV energy band. The background at balloon altitude is fully understood and its rate, energy spectrum and zenith dependence turn out to be well described by the known atmospheric $\gamma$-ray flux. Other minor components have been successfully identified and quantitatively accounted for. A detection, albeit weak, of the Crab in the 1-10 MeV energy band has also been obtained; this is the first since COMPTEL results. The development of the LXeGRIT instrument is now at the same performance level as pre-COMPTEL balloon instruments when they were considered ready to be turned into a major satellite mission. Papers describing these results are in the advanced draft stage and/or have been submitted for publication; preliminary results have been presented at the ‘‘Astronomy with Radioactivity’’ $4^{th}$ Conference (Kloster Seeon, May 2003).

Aprile, Giboni, Majewski, Yamashita and Ni have designed and tested prototype xenon chambers operated in single (liquid) and dual (gas/liquid) phase to study the feasibility of the XENON concept. XENON is a new experiment for the direct detection of dark matter WIMPs based on a 1-ton Xe active target, distributed in an array of ten independent liquid Xe time projection chambers (LXeTPCs), operated in dual phase. The sensitivity goal of the full-scale experiment is $\sim 10^{-46}$ cm$^2$, about a factor 100 beyond that projected by the CDMS II experiment in Soudan. This sensitivity can be achieved through a combination of a large, active, self-shielded target, event localization in 3-D, low threshold ($\sim$16 keV recoil energy), and additional background discrimination ($>$99.5%) using the simultaneous detection of ionization and scintillation signals produced in pure LXe by a WIMP recoil. A two year R&D phase for XENON started in September 2002, with support from the National Science Foundation (NSF). Progress has been made and the development of a 10 kg detector is near completion. Its cryogenics system, based on a mechanical refrigerator to maintain the liquid xenon temperature, has been successuffly tested. A new proposal to NSF was submitted on October 3, 2003, for the construction of the 1st XENON detector module with a fiducial target mass in excess of 100 kg (XENON100). The 3 yr program, with a start date of October 1, 2004 envisions the detector to be operational and taking science data in a deep underground site by the close of the 3rd year. Both the Gran Sasso Laboratory in Italy and the SNOLAB in Canada are being considered for XENON100. Following commissioning and calibration runs, the operation of the XENON100 module for 3 months at a background level below $1\times10^{-5}$ cts/keVee/kg/day after rejection would provide a sensitivity of $\sim10^{-45}$ cm$^2$. This module would be a prototype for a 10 detector array, XENON1T, which would be capable of collecting 20 WIMP events/year assuming a WIMP-nucleon cross section of $\sim2\times10^{-46}$ cm$^2$. The XENON Collaboration, led by Columbia University, includes Princeton, Brown, Yale, Rice, and the University of Florida, as well as LLNL.

Work continues on the development of X-ray and gamma-ray optics for balloon and satellite-based experiments. Hailey, Koglin and graduate student Chonko are building the optics for the High Energy Focusing Telescope (HEFT), a collaboration between Columbia, CalTech, Lawrence Livermore National Lab (LLNL) and the Danish Space Research Institute (DSRI). HEFT is scheduled to fly in the spring of 2004 and will have 3 grazing-incidence telescopes operating in the 20-100 keV energy band. Primary targets of HEFT are continuum and line emission from supernovae and active galactic nuclei. The group also continues to work on the development of segmented, thermally-slumped glass optics for the Constellation-X Hard X-ray Telescope and other future space missions. This work involves additional collaboration with NASA Goddard Space Flight Center.

Hailey, Gahbauer, Koglin, and Yu are working, in collaboration with LLNL, on the gaseous antiparticle spectrometer (GAPS). GAPS is a novel approach to the detection of antimatter which exploits the characteristic decay X-rays formed when antimatter is captured in conventional matter, making exotic atoms. The ultimate goal of GAPS is to conduct a space-based, indirect search for dark matter, through the primary antideuterons produced in neutralino-neutralino annihilation. Currently a prototype detector is under construction and will be tested in an approved experiment in Japan at the KEK Research Facility in Tsukuba. The experiment is scheduled to begin in late February of 2004.

Hailey continues to be involved in the EXIST gamma-ray all sky survey mission, with primary interest in background and shielding issues. Hailey, Chonko and Koglin also participated in a joint Small Explorer proposal with CalTech, LLNL, JPL, UC Santa Cruz and DSRI. The NuStar proposal involves development and flight of a hard X-ray telescope array to conduct an extensive survey of AGN and the Galactic plane.

Rasmussen, Kahn and Paerels have continued to guide the instrument design and development effort for a dispersive spectrometer aboard Constellation-X, one of two Great Observatories in the Beyond Einstein initiative. In collaboration with groups at MIT and the University of Colorado, they have been involved in a wide range of technology investigations for this experiment, including grating optic fabrication, X-ray CCD development, and the overall instrument optical design. Currently two different optical design directions are under consideration (in-plane and off-plane dispersion geometries), of which each offer benefits. Optimization of the design, in which collecting area and spectral resolution are jointly maximized, is under way. A significant highlight of this program in the past year was a synchrotron grating reflectivity measurement campaign conducted at the Advanced Light Source at Lawrence Berkeley Laboratory, in which the first MIT fabricated test rulings for either grating flavor were measured in a flight-representative configuration.

Mukherjee, Bramel and Goldman 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. STACEE has detected the Crab nebula, and the active galaxy Markarian 421, and has observed several other active galaxies.

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