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

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This report covers the period September 1999 through August 2000 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, William Craig, Arlin Crotts, Karl-Ludwig Giboni, Eric Gotthelf, Charles Hailey, Jules Halpern, David Helfand, Stephen Kahn, Marc Kamionkowski, Laura Kay (Barnard), Karen Leighly, Lloyd Motz (Emeritus), Reshmi Mukherjee (Barnard), Robert Novick (Emeritus), Frederik Paerels, Joseph Patterson, Kevin Prendergast, Andrew Rasmussen, Malvin Ruderman, Daniel Savin, Edward Spiegel, Wilhelmus van der Veen, and Jacqueline van Gorkom and David Windt.

Lam Hui joined the faculty of the Physics Department and Marcella Carollo joined the faculty of the Astronomy Department.

The Astronomy Department introduced a Universe Semester at the Biosphere 2 and recruited three new faculty for the Columbia West campus, Karen Vanlandingham, Philip Yecko and Catherine Garmany.

Graduate students participating in research were Douglas Bramel, Tzu-Ching Chang, Xinzhong Chen, Jean Cottam, Alessandro Curioni, Akimi Fujita, Mario Jimenez-Garate, Stefano Giovanardi, Eilat Glikman, Ming Feng Gu, JaeSub Hong, Miranda Jackson, John Keck, Tomotake Kozu, M. Leutenegger, Yuexing Li, Kaya Mori, Nestor Mirabal, Don Neill, Ian Mulvany, John Peterson, Jacob Noel-Storr, Masao Sako, Joshua Spodek, Ben Sugerman, Robert Uglesich, Leven Wadley.

Undergraduates participating in research were Eve Armstrong, Miles Blanton, Maya Cohen (Barnard), Yosi Gelfand, Jamila Hussain (Barnard), Eve Locastro (Barnard), Scott Schnee, Vincent Schoefer, Will Serber, Dana Stern (Barnard), Gisela Telis, Jennie Watson-Lamprey and Debra Willensky (Barnard).

Xinzhong Chen, Ming Feng Gu, and Joshua Spodek received Ph.D. degrees.

Appointments during 1999–2000 were held by Adjunct Professors Michael Allison from GISS and Michael Shara and Mordecai MacLow from the American Museum of Natural History, Postdoctoral Research Scientists Ehud Behar, Fernando Camillo, Christina Chiappini, Valeri Egorov, Christian Knigge, Uwe Oberlack, Stephen Lawrence, Louis Tao and Limin Wang.

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

During 1998-2000 the activities of the Center for Backyard Astrophysics greatly expanded. This is a network of astronomers, primarily amateur, who do stellar photometry with small telescopes in their backyards. Columbia personnel included Patterson, Kemp, and Locastro. They 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. 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, and California. Most programs involve the study of cataclysmic binaries, justly famous for the many periods present in their light curves.

The most interesting result came from intense coverage of V803 Cen, a well-known CV with a spectrum dominated by helium. It was found that V803 Cen appears to be an essentially garden-variety dwarf nova, despite its exotica (ultrashort period, helium composition). The outbursts occur very often, about every 23 hr, which is why the pattern wasn't noticed before (because this is close to the traditional 24 hr sampling rate). They also found ''superhumps'' in the light curve during the star's bright state, and managed to resolve the orbital and the superhump periods. The latter is only 0.4% longer than P_{orb}, which implies a secondary (mass-losing) star of only $0.014 \pm 0.009 M_{\odot}$. Since the secondary is now losing mass at $\sim 10^{-9} M_{\odot}$/yr, this implies that it is evaporating on a timescale of 10^{7} years.

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

Uglesich, Mirabal, Sugerman, and Crotts isolated a sample of variable stars, mostly RR Lyraes, in the core of the globular cluster M3, by use of the technique of image subtraction. This demonstrates the extraordinary power of this technique, in that their sample, obtained in moderate seeing conditions at the (ground-based) MDM Observatory's 1.3-meter telescope, is more complete than a corresponding sample obtained over the same area using the *Hubble Space Telescope*.

Helfand, in collaboration with E. Moran (Berkeley), completed an extensive analysis of the hard X-ray luminosity per O-star from young stellar populations. They show that the accretion-powered binary population dominates the integrated X-ray luminosity in the 2-10 keV band, and that the luminosity per O-star varies by a factor of $\sim$10 among the galaxies of the Local Group. Contrary to previous work, the X-ray luminosity is *not* found to be a function of metallicity: the SMC and M31 have the same value. The implications of these results for the contribution of starbursts to deep X-ray source counts and the cosmic X-ray background are presented.

2. X-RAY & γ-RAY SOURCES

At low Galactic latitude, establishing the nature of the majority of the EGRET sources is a problem that continues to require intensive multiwavelength observational effort. The Columbia group made considerable progress this year by obtaining several probable identifications. Halpern, Helfand, Gotthelf, & Leighly discovered a likely neutron-star/SNR counterpart of 3EG J2227+6122 using ROSAT, ASCA, and the VLA. An unusual feature of this source is a highly polarized radio shell with a flat radio spectrum. The central X-ray counterpart is probably an energetic young pulsar, estimated to be at a distance of $\sim$3 kpc from its fitted column density. Halpern, Mirabal, M. Eracleous (Penn State U.), and R.H. Becker (U.C. Davis) reported a probable counterpart of the brightest unidentified EGRET source at intermediate latitude, 3EG J1835+5918. It is a weak, ultrasoft X-ray source with no optical counterpart to $V>25$, and probably a pulsar that is either older or more distant than the prototype, Geminga. It could be a Geminga-like pulsar, or even a recycled pulsar with a very high γ-ray efficiency. Mukherjee, Gotthelf, Halpern, and Tavani identified one of the two EGRET sources in the COS–B field 2CG 075+00 with a blazar behind the Galactic plane (3EG J2016+3657). A variable optical counterpart of this radio blazar was discovered, but a redshift has not yet been determined.

The MDM Observatory continues to pursue optical afterglows of γ-ray bursts (GRBs). Several GRBs were successfully imaged in 1999–2000. Most notably, the optical afterglow of the second most energetic event, GRB 991216, was discovered at MDM by Uglesich, Mirabal, and Kassin (Ohio State U.). Continued monitoring of its light curve revealed jet-like behavior. The program at MDM will be intensified following the recent launch of the HETE–2 satellite, and the increased event rate reported by the interplanetary network of spacecraft. A continuous update of observations of GRBs at MDM Observatory is maintained at http://www.astro.columbia.edu/groupresearch.html.

Oberlack has continued research on the interpretation of γ-ray line emission from radioactive ^{26}Al in collaboration with the group at MPE Garching, Germany. An upper limit derived for the nearest Wolf-Rayet star γ^2 Vel with CGRO/COMPTEL data constrains models of nucleosynthesis in very massive stars. The observed line emission from the Cygnus region has been studied in detail within the context of massive-star formation and refined models for the expected ^{26}Al lightcurve for several star-formation histories. These models can now be tested with other observables, such as Lyman-α flux and the size of the observed super-bubbles.

3. PULSARS, NEUTRON STARS, AND SUPERNOVAE

Lawrence, Crotts, Sugerman and Uglesich, along with P. Bouchet and S. Heathcote (CTIO) discovered the first signs of the rapid emergency of ''hot spot'' activity around SN 1987A due to the collision of the ejecta from the supernova explosion as it reached the previously existing circumstellar ring in the nebula around the exploding star. This marks the first such time such multiple sites of secondary explosions have been observed in meaningful detail around a newly forming supernova remnant. The Columbia/CTIO group observed these from the ground using the CTIO 4-meter telescope, and confirmed them with new and archival data taken with the *Hubble Space Telescope*.

Gotthelf is studying several X-ray sources at the centers of supernova remnants in order to understand the evolution of young neutron stars and their relationship to supernovae. Gotthelf, G. Vasisht (JPL/Caltech), and T. Dotani (ISAS, Japan) confirmed that 1E 1841–045, the 12-s anomalous X-ray pulsar (AXP) which lies at the center of the supernova remnant Kes 73, is spinning down at a remarkably rapid pace. The spin-down rate and flux are exceptionally stable; these findings all but eliminate an accretion origin for the X-ray emission and strongly favor the ''magnetar'' model, with an enormous implied magnetic field of 7×10^{14} G. Along with D. Chakrabarty (MIT) and V. Kaspi (McGill), Gotthelf and Vasisht are monitoring the long-term timing stability of the young anomalous X-ray pulsar in the SNR Kes 73 using a set of RXTE observations. These observations span 2 years and a preliminary phase-connected timing solution confirms the remarkable spin-down stability of this object. This measurement, still in progress, will yield the all important braking index thus distinguishing among various NS energy loss models and placing strong constraints on the timing noise and glitches of this young pulsar.

Gotthelf discovered a 300 ms X-ray pulsar associated with the young Galactic supernova remnant Kes 75, one of the few examples of a shell-type remnant with a central compact radio core. This serendipitous pulsar, PSR J1846–0258, was found using RXTE data originally obtained for the purpose of studying a nearby anomalous X-ray pulsar. The new pulsar was subsequently located to the core of Kes 75 using archival ASCA imaging data. Timing analysis implies a characteristic age of only 700 yrs, consistent with the age of Kes 75, suggesting that PSR J1846$-$0258 is the youngest known pulsar. The rapid spin down of this pulsar is likely the result of torques from a large magnetic dipole of strength $\simeq5\times10^{13}$ G, just above the so-called quantum critical field. PSR J1846–0258 resides in this transitional regime where the magnetic field is hypothesized to separate the regular pulsars from the so-called magnetars.

Most recently, Helfand, Gotthelf, and R.H. Becker have observed Kes 75 with the Chandra X-ray Observatory using the ACIS CCD camera. The high-resolution X-ray image of the supernova remnant is remarkably similar to that seen in the radio. The new data set will allow the pulsar to be located more precisely and will likely confirm PSR J1846–0258 as a Crab-like pulsar, albeit one whose period, spin-down rate, and spin-down conversion efficiency are each an order-of-magnitude greater than those of the Crab, most likely as a result of its extreme magnetic field. The association of a shell-type remnant in Kes 75 with a coeval pulsar provides strong evidence that neutron stars are born in supernova explosions. Using existing and planned monitoring observations with RXTE, Gotthelf, Vasisht, Chakrabarty, and Kaspi intend to analyze the long long-term timing evolution of the Kes 75 pulsar. These observations span 2 years and will likely allow a phase connected timing solution if the spin down proves stable. This measurement could yield a value of the braking index and distinguish among various NS energy

loss models. Conversely, if timing noise and/or glitches are evident, these provide important probes of NS structure.

Gotthelf, Vasisht, B. M. Gaensler (MIT), and K. Torii (Osaka U.) continue their study of AX J1845−0258, a 7-s ASCA pulsar which strongly resembles AXPs. A dedicated VLA search at 5 and 8 GHz, centered on the location of the pulsar, revealed a previously unknown young ($\lesssim$8,000 yr-old) supernova remnant, G29.6+0.1. New ASCA data confirmed the dramatic reduction in X-ray flux from the pulsar and reveal a faint X-ray point source, AX J184453.3−025642, within the pulsar's error circle. This X-ray source is surrounded by a partial shell of emission coincident with the radio remnant. A program to monitor this pulsar for further activity is in place with RXTE. If the pulsar flux is found to increase, a new detection of pulsation may provide the critical period derivative measurement to determine the nature of the 7-s pulsar.

Along with colleagues M. Roberts (McGill), Kaspi, M. Pivovaroff (MIT) and N. Kawai (ISAS), Gotthelf is studying Chandra observations of the young supernova remnant G11.2−0.3. This SNR is proposed as counterpart of the historical supernova of A.D. 386, one of only eight historical supernovae recorded in the past 2000 years. It contains a fast (65 ms) spin-powered X-ray pulsar with a characteristic age of 24,000 years, much older than the SNR. The Chandra ACIS imaging observation cleanly separates the X-ray emission from the pulsar, plerion, and shell. Astrometric and spectral analyses of the pulsar and shell will provide critical constraints on the distance and age of the system, thereby allowing the evidence for an association with SN 386 to be evaluated.

Helfand, Halpern, and Gotthelf obtained two target-of-opportunity observations of the Vela pulsar with the Chandra Observatory 3.5 and 35 days after the largest glitch ever recorded for this object. The images show a spectacular, highly structured nebula; the dominant arc brightens significantly between the two observations. They derive the first high signal-to-noise X-ray pulse profile for the pulsar and show that neither the pulse shape nor intensity change over the month following the glitch. A pointing one year after the glitch is now scheduled to search for changes on longer timescales as energy dissipated in the interior at the time of the glitch diffuses to the surface.

4. ACTIVE GALACTIC NUCLEI

Halpern and Eracleous 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, primarily 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's investigation into the astrophysics of Narrow-line Seyfert 1 galaxies (NLS1s) continued this year. The primary work during this year, in collaboration with Jules Halpern, has been the analysis and interpretation of HST spectra from two extreme Narrow-line Seyfert 1 galaxies (NLS1s) IRAS 13224−3809 and 1H 0707−495. The principal observational result is that the high-ionization lines, including CIV, Lyα, NV and SiV are much broader than the low ionization lines including MgII and Hβ. While the trend for high ionization lines to be broader than low ionization lines has been known previously, these spectra show an extreme of this phenomenon. Furthermore, the high-ionization lines are strongly blueshifted; they have nearly no emission to the red side of the rest wavelength. Again, the tendency for the high ionization lines to be blueshifted compared with the low ionization lines has been known before, but these spectra show the extreme of this phenomenon. The observational results are most simply compatible with the interpretation that the emission lines are produced in a disk-wind system: the high-ionization lines are produced in a wind coming off the disk, probably accelerated by resonance-line driving as is inferred in CVs and hot stars, and the low ionization lines are produced in the low velocity material at the base of the wind or in the disk itself. The disk is optically thick, so emission is only seen from the wind coming toward us; hence the strong blueshifts imply terminal velocities greater than 10,000 km/s (Leighly 2000).

The results of the BeppoSAX observation of the bright Narrow-line Seyfert 1 galaxy have been analyzed in collaboration with Andrea Comastri and the other members of the BeppoSAX collaboration on NLS1s (Comastri *et al.* 2000). The continuum turns out to be complex and includes a power law plus a soft excess component; furthermore, there is no strong evidence for an emission line at 1 keV previously reported from the ASCA data when the continuum complexity is taken into account.

Multiwavelength data obtained during the period 1992–1998 from the luminous NLS1 RX J2217.9-5941 were compiled and analyzed by Grupe, Thomas & Leighly 2000. It was found that this object was bright in the ROSAT All Sky Survey, but had faded by a factor of more than 30 later when it was observed twice by the ROSAT HRI and once using ASCA. The ASCA data were hampered by low signal to noise and contamination by nearby sources; however, indications are that the spectrum is steep, and thus, although the object is deficient in X-rays, it does not appear to be absorbed.

Several new results were presented at the RXTE workshop held in NASA Goddard Space Flight Center in March. Power spectra from RXTE monitoring observations of the luminous AGN Fairall 9 and 3C 390.3 were compared. These objects have nearly the same hard X-ray luminosity,

so one naively expects the variability properties to be the same. Instead the variability power spectrum in 3C 390.3 is significantly steeper based on ROSAT monitoring observations made in 1995 and RXTE monitoring observations started in 1999. 3C 390.3 is suspected to have an Advection Dominated Accretion Flow (ADAF), while Fairall 9 may have a thin disk, and the difference in variability behavior may be a direct consequence of the difference in the X-ray emitting region.

The results of an observation using BeppoSAX of the nearby Seyfert 2 galaxy NGC 6300 were presented. The RXTE observation revealed a huge equivalent width iron line and flat continuum, providing persuasive evidence that NGC 6300 is a bright example of a Compton-thick Seyfert 2 galaxy. The BeppoSAX observation, made 2.5 years later, found NGC 6300 in a much different spectral state. The 2-10 keV flux had increased by a factor of two and the X-ray absorption had become Compton-thin. The AGN was strongly detected up to 100 keV with the PDS, and rapid hard X-ray variability was also observed. This result may provide evidence that the intrinsic source flux increased dramatically between the two observations; however, a decrease in the column density cannot be ruled out. A soft X-ray spectral component, not detected in the Einstein IPC observation, appeared as well. Results from an optical spectropolarimetric observation were made at the CTIO 4-meter telescope in June 1999 using a visitor spectropolarimetry module. The continuum is about 0.8% polarized, but there is no evidence for enhancement near emission lines that would indicate the presence of a hidden broad-line region.

5. SURVEYS

Helfand and his principal collaborators R. Becker and R.L. White (STScI) completed another observing session for the *FIRST* survey with the VLA. To date, 7998 deg^2 have been mapped to a sensitivity threshold of 1 mJy at 20cm and 722,000 sources have been located with positional accuracies of better than $1''$.

Helfand and Glikman with their *FIRST* collaborators have matched the *FIRST* radio catalog to the 2MASS catalog of near-IR sources in a search for the putative population of highly reddened quasars. They have found 64 objects detected at both radio and IR wavelengths which are absent on the POSS-I plates; all have $B-K>5$. A dozen objects have been imaged at K-band with Keck, and the majority are stellar. A spectrum of the most extreme object with $B-K>8$ shows a highly reddened $z=2.2$ quasar that is gravitationally lensed. Followup observations of the remaining objects in the sample are planned.

Helfand and Kinkhabwala, in collaboration with F. Harrison (Caltech), have begun a major program to identify serendipitous faint X-ray sources in Chandra fields. To date, they have produced a catalog of over 300 sources detected in the 2-9 keV band in a dozen fields and have obtained deep ($R\sim 24-25$) optical images of all these fields. Spectroscopy of the optical counterparts has been completed for about one-quarter of the objects and substantial additional observing time has been scheduled. They find a wide variety of counterpart types ranging from normal and starbursting galaxies to quasars and Seyfert galaxies. The goal is to construct a sample of over 1000 objects in order to define the logN-logS for different source classes and make a definitive determination of the contributions of each class to the X-ray background. They are also studying both the clustering of X-ray sources in the fields and the apparently large-amplitude cosmic variance apparent in interfield comparisons; with Scharf, they are also searching for correlations between the field galaxy counts and structure in the diffuse background emission.

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 D configuration were completed this summer; C- and B-configuration data will be collected in the coming year. In collaboration with a group from the University of Leicester, they will be mapping the same region with the XMM-Newton Observatory, providing a dramatic new view of stellar birth and death in the Galaxy.

6. GALAXIES AND LARGE SCALE STRUCTURE

Carollo, M. Stiavelli (STScI), P.T., de Zeeuw (Leiden), M. Seigar (STScI) and H. Dejonghe (Gent) performed an HST/NICMOS NIR survey in H and J for a sample of 69 spiral galaxies for which they already had WFPC2 V images. The V-H color distribution of bulges with an $R^{1/4}$ light profile was found to peak around 1.3 magnitudes, with a sigma of about 0.1 magnitudes. For a solar metallicity, these values correspond to stellar ages of about 6 ± 3 Gyrs. In contrast, the V-H color distribution of bulges with an exponential light profile peaked at about 0.9 and has a sigma of about 0.4 mags. This likely implies significantly smaller ages and/or lower metallicities for a significant fraction of the stars in the exponential bulges compared to the $R^{1/4}$-law spheroids. Photometrically-distinct nuclei (previously detected in the optical) were detected in the NIR in the centers of many spiral galaxies, including systems with an exponential bulge. Most of the central nuclei hosted by the exponential bulges were found to have V-H and J-H colors which are compatible with relatively unobscured stellar populations. Assuming no or little dust effects, ages of about or in excess of 1 Gyr were derived for these nuclei, which in turn imply masses of about a few 10^6 to a few $10^7 M_\odot$. This HST photometric survey has shown that the structures which are currently formed inside the disks are quite dissimilar from the old elliptical-like spheroids which are hosted by the early-type disks.

Carollo and S.J. Lilly (Herzberg Institute) measured the emission line ratios in a sample of 34 CFRS star-forming galaxies with redshifts between $0.5<z<1.0$, and computed their metallicities by means of the empirically-calibrated R_{23} metallicity estimator introduced by Pagel & Edmunds (1979). A preliminary analysis, focussed on a high-Hβ selected sample of 15 galaxies, showed that the metallicities of these galaxies appear to be remarkably similar to those of local galaxies selected in the same way, suggesting that there has been little change in the relationship between metallicity and line- and continuum-luminosity from redshift about 1 to today. This work does not support the idea that the $0.5<z<1.0$ (high-Hβ) galaxies are dwarf galaxies brightened by

large bursts of star-formation, as had been suggested from previous studies. Rather, these findings are more consistent with a picture in which these systems are the progenitors of today's massive metal-rich galaxies.

W. Evans (Oxford), Carollo and P.T. de Zeeuw (Leiden) used scale-free triaxial halo models with flattish rotation curves to compute the differential detection rate for energy deposited by rare WIMP-nucleus interactions. Although triaxiality and velocity anisotropy change the total rate by only about 20%, they have a substantial effect on the shape of recoil spectrum. In particular, the study showed that the amplitude of the annual modulation signal depends sensitively on the velocity anisotropy, being weaker in the radially anisotropic halo models, and that even the sign of the signal can be changed. Restricting attention to low energy events, as some experimental groups do, this study showed that the maximum WIMP rate could occur in December rather than in June.

G. Verdoes (Leiden/STScI), R. van der Marel (STScI), Carollo and P.T. de Zeeuw (Leiden) studied the kinematics of the central gas disk in the counter-rotation-core galaxy IC1459, and found in this system a black hole mass in the range 1-4 $10^8 M_\odot$. This implies a black hole mass to galaxy mass ratio in the range $0.4-1.5\times10^{-3}$, which is not inconsistent with results obtained for kinematically-normal galaxies.

Chiappini and Carollo are studying optical spectra for a sample of about 50 bulges to derive metallicity/age sensitive absorption indices and emission line fluxes (and ratios). This study will provide a map of the local stellar population (age and metallicity) properties in bulges as a function of Hubble type, and of their formation timescales. The stellar population properties will be also investigated as a function of the ISM properties. The sample was selected from the one investigated by Carollo *et al.* (1997, 1998) with HST. The availability of information on the nuclear scales will allow to relate the central properties of bulges (nuclei) to their large scale properties.

Chiappini has also been working in a chemical evolution model for the Milky Way formation. Chiappini, F. Matteucci (U. di Trieste) and D. Romano (SISSA/ISAS) (2000a,b) present theoretical results on the galactic abundance gradients of several chemical species for the Milky Way disk, obtained using an improved version of the two-infall model of Chiappini, Matteucci and Gratton (1997) that incorporates a more realistic model of the galactic disk and halo. This improved model provides a satisfactory fit to the elemental abundance gradients as inferred from the observations and also to other radial features of our galaxy (i.e., gas, star formation rate and star density profiles). They conclude that a relatively short halo formation timescale ($\simeq$ 0.8 Gyr), in agreement with recent age estimates for the age differences among Galactic globular clusters, coupled with an ''inside-out'' formation of the Galactic disk where the innermost regions are assumed to have formed much faster than the outermost ones, represents, at the moment, the most likely explanation for the formation of the Milky Way. Chiappini also explored the effects of adopting an initial mass function variable in time on the chemical evolution of the Galaxy (Chiappini & Matteucci, 2000a; Chiappini *et al.* 2000) and concluded that an IMF which is a strong function of time will not lead to a good agreement with the observational constraints, suggesting that if the IMF varied this variation should have been small. The two-infall model was also applied in the study of the evolution of the light elements in the Galaxy (Chiappini & Matteucci 2000b); to constrain the mass surface density in the local disk (Romano *et al.* 2000) and to investigate the evolution of oxygen abundance in the Galaxy (Matteucci & Chiappini 2000).

Crotts is principle investigator of an international collaboration (MEGA: Microlensing Exploration of the Galaxy and Andromeda) to determine if large, dark matter objects, i.e., MACHOs compose a large fraction of the mass of the Andromeda Galaxy, M31. They recently wrote several papers describing their survey and its utility in solving the spiral galaxy halo dark matter problem, and expect to have preliminary results in the near future.

Crotts, along with D. Vanden Berk, C. Stoughton (FNAL), D. Tytler and D. Kirkman (UCSD) have shown that many of the redshift clumps of galaxies seen in the Hubble Deep Field are contained in what appear to be large sheets (more than about 10 Mpc across) of gas containing heavy elements, e.g., magnesium. In the process of this investigation, they have provided the most complete known sample of quasars in the vicinity of the HDF.

Hailey, Craig and Neill have been studying the 'beta problem' in Abell 262 and have just had a paper accepted (Neill *et al.* 2000) with the same title. They used the Automated Multiobject Spectrograph at the 3 meter telescope at Lick Observatory (built by Hailey, Craig and J. Brodie at UCSC) to obtain a large sample of galaxy redshifts within Abell 262. Combining this data with ROSAT HRI and ASCA data they were able to construct a comprehensive picture of the cluster. They have shown that there is no beta problem in Abell 262 (as had been previously reported) but that the actual beta is a factor of two different than that previously reported. This completely changes the picture of the cluster in terms of the relative temperature of galaxies and gas and has important implications for models of galaxy-gas interactions.

Helfand and Scharf, in collaboration with Lacy (IGPP), have begun a program to study large-scale structure in the redshift interval 0.2-1.2 using hosts of classical radio galaxies as tracers of dense regions of the Universe. They are mapping 80 deg^2 in I-band at MDM, and will identify elliptical hosts of *FIRST* radio sources for followup spectroscopy. A pilot study showed that with only $\sim$30 redshifts, a significant spatial clustering was detected; the goal is to obtain several hundred identifications in order to observe directly the evolution of structure over the redshift interval studied.

Helfand, in collaboration with Leighly, E. Blanton (UVa), and the *FIRST* team, completed an imaging and spectroscopic study of 40 bent-double radio sources which form a complete, magnitude-limited sample. They find many such objects reside in clusters or groups, with the richest, lower-redshift portion of the sample being detected in the ROSAT All Sky Survey. However, some bent doubles appear in poor environments, suggesting either that they lie in fossil groups

(in which the host has cannibalized all its companions but hot intracluster gas remains) or that alternative mechanisms for bending the radio lobes are required.

Helfand and Chang in collaboration with Refregier (Cambridge) continued their attempts to extract a weak-lensing signal from the *FIRST* data. A detection consistent with the expected signal on scales of $20 - 200'$ is seen, although the systematic effects have yet to be fully characterized. They are now pursuing a technique which would extract the signal directly from the uv data, greatly simplifying the correction of systematic effects.

The structure of clusters of galaxies and the evolution of galaxies in those environments, from the low density outer parts to the dense inner cores is probed in HI by van Gorkom. Survey time has been allocated at the VLA to study a sample of nearby clusters. The project, done in collaboration with H. Bravo-Alfaro (Guanajuato), K. 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), aims at getting complete HI imaging data for 12 clusters covering a redshift range from 0 to 0.2. This 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, 2000). 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 there is also 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.

A number of interesting results were obtained for the Virgo Cluster. Li and van Gorkom imaged the HI in the giant elliptical M86. This galaxy has an extended asymmetric X ray halo and spatially coincident HI that is kinematically decoupled from the stellar kinematics. They conclude that the HI has most likely cooled out of the X ray gas (Li and van Gorkom, 2000), after it has been shocked by an ICM-ISM interaction. J. Kenney (Yale), van Gorkom and B. Vollmer (MPA, Bonn) have imaged the HI and radio continuum in the highly inclined Virgo spiral, NGC 4522. The images reveal extraplanar HI, which is sharply cutoff in the disk, and a huge non thermal radio plume, stretching out from the disk over at least 14 kpc. These distributions look remarkably like the SPH simulations by Vollmer, which suggests that the galaxy was stripped on its way through the core of Virgo and the current gas morphology shows gas falling back onto the galaxy.

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. (Chang *et al.* 2000)

M. Balcells (IAC, Tenerife), van Gorkom and R. Sancisi (Bologna) analyzed the HI distribution and kinematics in the shell elliptical NGC 3656. For the first time stellar kinematics was obtained for part of a shell. The stellar velocities agree with the HI kinematics. Thus for NGC 3656 the HI is truly associated with the shell. This fits in with a very extensive database obtained by D. Schiminovich (Caltech), van Gorkom and J. van der Hulst (Kapteyn Institute) on shell galaxies. Many of these are found to be HI rich and the morphology suggests a common origin of the HI and stellar tidal features.

Giovanardi, van Gorkom with J. Hibbard (NRAO) and J. Stocke (Colorado) continued their search for HI from the environment of nearby Ly alpha absorbers. Results were obtained for another 6 absorbers. Only one HI emitter was found, at large projected distance from the absorber. The long term goal is to see whether the presence of a Ly alpha absorber affects the HI detection statistics in its environment and whether anything can be said about possible association between absorber and emitters.

M. Blanton, van Gorkom and S. Baum (STScI) searched for HI absorption in a sample of radio loud ellipticals. Several new detections were made, but the results are more complicated than the simple infall picture previously found by van Gorkom *et al.* (1989).

7. X-RAY SPECTROSCOPY

Last year saw the advent of high resolution spectroscopy in X-ray astronomy, with the successful launches of the Chandra and XMM-Newton observatories, both of which carry sensitive, high resolution diffraction grating spectrometers, capable of carrying out observations on a routine basis. The Columbia Astrophysics Laboratory, having built the arrays of diffraction gratings for the Reflection Grating Spectrometer (RGS) on XMM-Newton, under the direction of Steve Kahn, is deeply involved in the calibration and operations of this instrument, as well as the interpretation of the first spectra to be obtained with it (the instrument team involves Kahn, Rasmussen, Behar, and Paerels, and Cottam, Sako, Peterson, and Leutenegger).

It is not an exaggeration to say that this new field of study has so far exceeded all expectations. Virtually every spectroscopic observation obtained at Columbia over the last year has yielded a surprise, and the results are starting to affect almost every field of observational high energy astrophysics. We were able to build on previous experience, gained with the analysis of lower resolution CCD spectra, combined with a systematic program aimed at the development of the quantitative foundation of astrophysical X-ray spectroscopy.

Sako, Kahn, Paerels, and their collaborators D. A. Liedahl and P. S. Wojdowski (Lawrence Livermore National Laboratory) have carried out detailed spectroscopic studies of massive X-ray binaries using the CCD spectrometers onboard the ASCA Observatory. They have re-examined archival data from Vela X-1 and Cen X-3 in the context of detailed atomic physics calculations and simple stellar wind

models. In Vela X-1, where the X-ray luminosity is much lower than in the Cen X-3 system, the stellar wind is clumpy and consists of numerous cold clouds embedded in a much hotter medium. On the other hand, the stellar wind in Cen X-3 is determined to be more homogeneous. The method is general and applies to a wide class of objects. It has also been successfully applied to the spectral analysis of the ASCA spectrum of a Seyfert 2 galaxy, the Circinus. In this system, the authors conclude that the X-ray emission lines are formed in a medium extending out to a few hundred parsecs from the center of the galaxy, and derived quantitative constraints on the spatial distribution of material, which will be essential for distinguishing between inflow and outflow models of AGNs.

In the following, we list the highlights from this first year of X-ray astrophysical spectroscopy, based on data obtained both with the XMM-Newton RGS, as well as the grating spectrometers on Chandra.

Kahn, Cottam, Sako, and Paerels have studied a sample of accretion powered sources, both galactic and extragalactic, with collaborators at the Space Research Organization of the Netherlands (SRON), the Mullard Space Sciences Laboratory (MSSL, UK), and Lawrence Livermore National Laboratory. An early spectrum of the massive binary Cygnus X-3 showed a pure recombination-driven discrete emission spectrum, with a number of novel spectroscopic diagnostics clearly resolved for the first time. The edge-on binary EXO0748-67 likewise showed a novel line spectrum, displaying emission from high-density photoionized gas which is evidently distributed in a flattened, disk-like geometry (far) above and below the accretion disk. A high resolution spectrum of the Seyfert 2 galaxy Mkn 3 shows slightly extended X-ray line emission from the nuclear region, indicative of a warm medium in photoionization equilibrium, with parameters possibly in the right range for it to be the 'warm absorber' now seen in high resolution spectra of Seyfert 1 galaxies. One such galaxy, IRAS13349+2438, shows evidence for at least two distinct regions of ionization in its X-ray absorption line spectrum, with kinematics consistent with an accelerated outflow away from the black hole.

Most spectacularly, the Seyfert 1 galaxies MCG-6-30-15 and Mkn 766, in high resolution spectra obtained with the RGS, do not show the expected strong continuum absorption in partially ionized gas (with large absorption edges due to H- and He-like oxygen, as inferred from CCD spectroscopy). Instead, the spectrum appears consistent with relativistically distorted line emission from highly ionized oxygen, nitrogen, and carbon, arising in material orbiting close to the horizon of a massive black hole.

Behar, Cottam, Kahn, and collaborators at SRON, MSSL, and the Paul Scherrer Institute (PSI, Switzerland) have carried out a systematic study of the first few bright coronal spectra, the Chandra High Energy Transmission Grating Spectrometer spectrum on Capella, and the RGS spectra of HR1099 and Capella. These spectra, apart from their astrophysical interest, constitute a 'benchmark' of our understanding of X-ray spectroscopy, in arguably the simplest of astrophysical settings, at least in terms of the relevant excitation mechanism. From these studies these authors conclude, very roughly speaking, that the current understanding of spectral formation in a collision-dominated plasma appears to be accurate in its dominant features.

Peterson and Paerels, with collaborators at SRON, Saclay (Paris), MPE (Munich), GSFC, and Cambridge University (UK), have analyzed the first resolved soft X-ray spectra of cooling flows in clusters of galaxies, obtained with the RGS, the only instrument that is currently capable of obtaining wavelength-resolved soft X-ray spectra on these objects. In the first four strong cooling flow clusters observed, they find that they can spectroscopically trace gas cooling all the way down to $kT \sim 1-2$ keV, but that the gas disappears at lower temperatures. The possible explanations for this observation, and the implications for the thermodynamics of cooling gas in clusters of galaxies, are currently being investigated.

Rasmussen, Behar, Cottam, Kahn and collaborators at SRON and MPE, started the analysis of a large, systematic soft X-ray spectroscopic survey of bright, compact Supernova remnants in the Magellanic Clouds. These objects are small enough that the RGS can still resolve their soft X-ray emission line spectra, which opens the possibility to study the properties of the hot shocked gas in detail (degree of equilibration, excitation mechanism, abundances, velocity fields, etc.). Among the early results from the study is the finding that in the very young, oxygen-rich SMC remnant 1E0102-72.3, the ratio between the Lyα emission lines, and the higher corresponding series members, in all the H-like ions from C VI to Ne X, appear to be well below their values for electron impact excitation, whether in or out of collisional equilibrium. A possible explanation invokes excitation by charge exchange on neutral H at the interfaces of cool embedded clouds within the remnant.

Kahn, Cottam, Leutenegger and collaborators studied the high resolution spectrum of the O star ζ Pup. The RGS spectrum is dominated by very strong, Doppler-broadened emission lines from all abundant elements, up to Si, with particularly strong emission from N, indicative of CNO burning. The so-called He-like 'triplets' of N, O, and Ne, indicate that these ions are bathed in the intense photospheric UV field of the O-star, which measurably affects the level populations and hence the X-ray emission spectrum. Constraints on the intensity of the stellar UV field, and the kinematics inferred from the line profiles, combine to produce a model for the stellar wind and its X-ray emission that is consistent with current theoretical models to a remarkable degree.

With the RGS, we are now also acquiring the first sensitive photospheric emission spectra from compact objects. The first such spectrum was that of the famous source CAL 83 in the LMC, a white dwarf which supposedly undergoes stable nuclear burning of accreted material at it surface. Paerels, Rasmussen, and collaborators at SRON find that the spectrum shows very significant spectroscopic structure, most likely due to numerous absorption lines from the mid-Z element L-shells. While a quantitative interpretation of this spectrum must await dedicated radiative transfer calculations, it is abundantly clear from a simple inspection of the spectrum that 'blackbody fits' to spectra of this kind will (or should) be a thing of the past. Strangely enough, and somewhat disappointingly, the reverse turns out to be true for the

spectrum of the isolated neutron star RXJ0720.4-3125. Paerels, Mori, and collaborators at MPE, MSSL, the University of Strasbourg, and SRON, show that the spectral shape is close to a blackbody shape, without any strong photospheric absorption features, which will make it very difficult to measure the fundamental parameters of this object (or of any other isolated neutron star, if this object is at all characteristic).

Finally, as a byproduct of sensitive spectroscopic studies of the Low-Mass X-ray Binary X0614+091 and the Crab Pulsar with the Low-Energy Transission Grating Spectrometer on Chandra, the first resolved interstellar X-ray absorption spectra were obtained. Paerels, Kahn, Savin, and collaborators at SRON and MPE found narrow oxygen absorption lines in the spectrum of X0614+091, which appear to indicate the presence of oxygen in at least two phases, atomic and molecular, along this line of sight. Likewise, Noel-Storr, Paerels, and Kahn identify multiple interstellar oxygen absorption features in the spectrum of the Crab Pulsar, which are currently under investigation.

8. LABORATORY ASTROPHYSICS & INSTRUMENTATION

Aprile, Curioni, Egorov, Giboni, Hussain, Oberlack, Zhang and S. Ventura (INFN–Padova University, Italy) continued their work on the Liquid Xenon Gamma-Ray Imaging Telescope (LXeGRIT) project. A considerable effort has been devoted to data analysis, both of the '99 LXeGRIT balloon flight and of laboratory calibration data. The results, concerning the spectroscoscopic and imaging performance and the performance at balloon altitude during the '99 flight, have been presented at the SPIE2000 conference and at the *Frontier Detectors for Frontier Physics* conference (Isola d'Elba, Italy).

This extensive analysis work, followed by various improvements of the instrument, eventually led to a new balloon flight on October 4, 2000, from Fort Sumner, NM, the main changes being a trigger fully optimized for the MeV region, a ''naked'' LXe TPC (the active shield used during the '99 flight having been removed), fastened data acquisition and improved on–board data storage.

It has been a great turn–around flight with more than 24 hours at float altitude (about 27 hours including ascent), and the LXeGRIT instrument performed perfectly in all its parts. The flight was terminated on October 5 late afternoon, to avoid the risk of a cut-down at night. The main science focus was imaging and polarization studies of the Crab nebula, but other strong sources such as 3C273 or Cygnus X-1 have also been in the field-of-view. There are very interesting, very high energy, cosmic ray events in the sample. A total of almost 40 GB of event data were collected, of which about 80% have been stored on–board, and the rest downlinked through two 500 kbps telemetry channels. The total LXeTPC trigger rate, remained nicely constant around 700 Hz, after the expected increase during ascent. It looks like a great success for a new material like LXe in a high radiation environment as the nearby space.

The payload is now back at the Columbia Astrophysics Laboratory, in perfect working conditions and next flights can be planned. With its large FOV and good sensitivity in a broad energy band, LXeGRIT is well suited for imaging observations of compact sources in the Galactic Center and bulge, and for a study (it would be the first time with an imaging telescope) of the positron annihilation line and continuum emission.

Spectral and Compton imaging analysis of the recent flight data is in progress and exciting results are expected. More information and pictures of the detector and the flight campaign can be found at http://www.astro.columbia.edu/~lxe/lxegrit. Along with a continuation of a flight program with LXeGRIT, the Columbia team is continuing the research and development program on a ''warm'' liquid xenon TPC (or high pressure gaseous TPC), as proposed in their last NASA High Energy Astrophysics SR&T research program, to match the requirements of a next generation Advanced Compton Telescope for a sensitive nuclear line astrophysics mission.

Crotts has finished construction of a 8192×8192 pixel CCD imager for use on the MDM Observatory's 1.3-meter and 2.4-meter telescopes. This is one of the largest CCD imagers in the world and has already gone into regular service on both telescopes. It offers a field-of-view of 45 and 25 arcminutes, respectively, on the two telescopes, and is well-matched to the subarcsecond seeing performance, particularly on the 2.4-meter telescope.

Mukherjee and D. Bramel worked on *STACEE* (Solar Tower Air Cherenkov Effect Experiment), a ground-based detector that is sensitive to high energy γ-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* reported the detection of the Crab nebula, 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, Dana Stern, and M. Tavani (IFCTR-CNR) worked on unidentified EGRET sources, specifically the two sources in the COS-B γ-ray field of 2CG 075+00. Work on several of these mysterious unidentified high energy sources is currently in progress. Mukherjee also worked on the spectral analysis of several active galaxies observed by EGRET.

Behar has continued his works on fundamental atomic physics, investigating quantum interference effects in photorecombination processes, electron density effects on dielectronic recombination, and spectroscopic analysis of laser produced plasmas of heavy metals.

Savin, Kahn, and Gu and their collaborators P. Beiersdorfer, B. R. Beck, G. V. Brown, D. A. Liedahl, and J. H. Scofield (Lawrence Livermore National Laboratory) have developed a a technique for producing a Maxwell-Boltzmann electron energy distribution using an electron beam ion trap (EBIT). The technique was implemented on the Lawrence-Livermore EBIT to simulate Maxwellian plasmas. To verify the fidelity of the quasi-Maxwellian, they have measured line emission due to dielectronic recombination (DR) and electron impact excitation (EIE) of heliumlike neon, magnesium, and argon for a range of simulated electron temperatures.

The ratio of DR to EIE lines in heliumlike ions is a well understood electron temperature diagnostic. The spectroscopically inferred quasi-Maxwellian temperatures are in excellent agreement with the simulated temperatures.

At a recent conference, Savin presented a review of the status of dielectronic recombination (DR) rate coefficients used for modeling cosmic plasmas. He gave a brief overview of theoretical and experimental studies of DR. He also showed results which demonstrated the astrophysical importance of accurate DR rates for studies of the intergalactic medium.

Kahn, Savin, and Gu and their collaborators P. Beiersdorfer, G. V. Brown, D. A. Liedahl, C. W. Mauche, and S. B. Utter (Lawrence Livermore National Laboratory) J. K. Lepson (University of California at Berkeley), and J. J. Drake and B. J. Wargelin (Harvard-Smithsonian Center for Astrophysics) reported on recent measurements carried out using the Lawrence-Livermore Electron Beam Ion Trap. Using spectroscopic equipment optimized for laboratory astrophysics, they are performing systematic measurements of the line emission from astrophysically relevant ions in the wavelength band between 1 and 400 Å important to X-ray missions such as Chandra, XMM-Newton, and EUVE. Obtained in a controlled laboratory setting at electron densities similar to those found in stellar coronae, the data are used to test spectral modeling codes for accuracy and completeness. The effort of Kahn and collaborators includes the compilation of the iron L-shell emission from 6-18 Å and the iron M-shell emission lines from 50-200 Å . Many lines have been identified for the first time, and the measured fluxes from lines mission in the spectral modeling codes are assessed. The measurements also assess the accuracy of line excitation calculations, including direct electron-impact excitation, dielectronic recombination, and resonance excitation. These measurements yield a calibration of specific diagnostic line ratios.

At a recent conference Kahn and his co-workers P. Beiersdorfer, G. V. Brown, D. A. Liedahl, C. W. Mauche, and S. B. Utter (Lawrence Livermore National Laboratory) and J. K. Lepson (University of California at Berkeley) presented a report on detailed laboratory astrophysics measurements to produce spectral tables for the Fe VII - Fe XXIV line emission in the EUV wavelength band. Measurements are being carried out using the Lawrence-Livermore electron beam ion trap.

Savin has carried out a series of model calculations of the photoionized intergalactic medium (IGM) to determine the effects on the predicted ionic column densities due to uncertainties in the published dielectronic recombination (DR) rate coefficients. Based on his previous experimental work and a comparison of published theoretical DR rates, he estimates there is in general a factor of 2 uncertainty in existing DR rates used for modeling the IGM. Savin demonstrates that this uncertainty results in factors of $\sim$1.9 uncertainty in the predicted N V and Si IV column densities, $\sim$1.6 for O VI, and $\sim$1.7 for C IV. He shows that these systematic uncertainties translate into a systematic uncertainty of up to a factor of $\sim$3.1 in the Si/C abundance ratio inferred from observations. The inferred IGM abundance ratio could thus be less than $(\mathrm{Si/C})_{\odot}$ or greater than $3(\mathrm{Si/C})_{\odot}$. If the latter is true, then it suggests the metagalactic radiation field is not due purely to quasars, but includes a significant stellar component. Lastly, column density ratios of Si IV to C IV versus C II to C IV are often used to constrain the decrement in the metagalactic radiation field at the He II absorption edge. Savin shows that the variation in the predicted Si IV to C IV ratio due to a factor of 2 uncertainty in the DR rates is almost as large as that due to a factor of 10 change in the decrement. Laboratory measurements of the relevant DR resonance strengths and energies are the only unambiguous method to remove the effects of these atomic physics uncertainties from models of the IGM.

Gu, Savin and P. Beiersdorfer (Lawrence Livermore National Laboratory) have developed a theoretical formalism for calculating the anisotropy and polarization of photon emission due to a spiraling beam of electrons colliding with an ensemble of atoms or ions. For an axisymmetric beam with a given velocity angular distribution, the polarization and angular distribution of the resulting radiation can be characterized by the expansion coefficients of the distribution function in terms of Legendre Polynomials. They present simple expressions for dipole and quadrapole radiation and apply the results to the case of an electron beam ion trap.

Hailey, Craig, Windt, Koglin, and Jimenez-Garate are working on the High Energy Focussing Telescope (*HEFT*) balloon telescope. HEFT is γ-ray ray telescope designed for operation in the 20-70 KeV energy band and will have subarcminute angular resolution. It uses true focussing optics. Columbia is constructing the mirrors for *HEFT* using multilayer coated, thermally-slumped glass optics developed by Columbia and the Danish Space Research Institute. The detectors for *HEFT* are CZT pixellated detectors being developed at CalTech. Lawrence Livermore National Laboratory is working on the aspect reconstruction system. The *HEFT* team has already reported on the first images ever taken in the hard X-ray band (at 28 and 68 KeV) using a prototype optic (Craig *et al.* 2000). Currently Columbia is in the process of building the *HEFT* flight optics and has already constructed the gondola.

Hailey, Craig, Windt, Koglin, and Jimenez-Garate, in collaboration with DSRI are also working on a project to improve the performance of glass optics for use at higher energies and with even better angular resolution. Such optics are particularly suited for use in a Nuclear Line Telescope to observe radioactive Cobalt lines from young type Ia supernovae. The team has produced the first true image in the gamma-ray band ever taken (at $\sim$150 KeV) which will soon be reported in the literature. Columbia is also working in collaboration with CalTech on this project.

Hailey, Craig, Hong, and Keck are studying several compact galactic sources which emit gamma-rays using the γ-ray Arcminute Telescope Imaging System (*GRATIS*) flown by Columbia as well as data from other satellites. Keck's thesis is a study of GRS1758, and using data from GRATIS, BATSE, SIGMA, ROSAT, RXTE, VLA and ASCA he has constructed a comprehensive picture of the source over a long time baseline. He has been able to constrain model pa-

rameters for various theories of emission, in particular finding strong support for Advection Dominated Accretion Flow theories. A paper will be submitted this fall on the results. Hong's thesis is on GRATIS observations of 4U1700 and addresses the various conflicting temperature measurements of the source. A paper will be submitted this fall on this anlaysis as well.

Hailey, Mori, Craig, and Serber have also been working on a completely novel concept for detecting antiprotons and antiHelium. The technique involves the slowing down and capture of antiparticles in antiatoms with the subsequent detection of characteristic X-rays unique to the antiatoms formed. This technique provides an extremely clean positive signature for the detection of antimatter, and preliminary calculations indicate it is much superior to alternative techniques for detecting low energy antiprotons and analysis is also indicating the technique may be much better than use of magnetic spectrometers for detection of antiHelium. A paper will be submitted on the preliminary analysis this fall.

Hong, Hailey and Craig have been working on direct detection of dark matter. They are members of the United Kingdom Dark Matter collaboration (UKDMC) and are building the one ton liquid scintillator veto shield for the *ZEPLIN* III dark matter detector currently under construction in England. Working with Y. Gelfand they have made measurements to optimize the light collection of the shield design. The veto shield and *ZEPLIN* detector will be integrated next spring and then begin operating in the Boulby mine in England. Hong, Hailey and Craig, in collaboration with U. Sheffield have also completed studies of scintillation efficiency of liquid scintillators for dark matter detection. They have shown that liquid scintillators display a hitherto unexpected increase in scintillation efficiency at low recoil energy which make them possible dark matter detectors. They had previously been rejected because of the belief that their scintillation efficiencies were too small at low recoil energies. A paper has been submitted on this work (Hong *et al.* 2000).

Hong, Craig and Hailey continue their research on the use of neutron shields for space-based gamma-ray telescopes. They have completed a series of extensive tests of neutron shields using monochromatic neutrons and obtained excellent agreement between experiments and results of Monte-Carlo analysis. They have shown that such shields could be of great utility in future space missions such as *EXIST*. Their most recent results have just been published (Hong, Craig, & Hailey 2000).

Craig, Hailey and Hong continue to collaborate with Josh Grindlay at Harvard on the *EXIST* All-Sky Sky Gamma-ray Survey mission study (Grindlay et al. 2000). They participated in the recent mission study done at NASA/GSFC. Hong has also developed an improved scheme for imaging using coded aperture masks which solves some fundamental limitations in currently employed schemes. A paper on this work will be submitted this fall.

Windt is performing research directed at the development of high-performance multilayer coatings for high-energy astrophysics and solar physics. Depth-graded multilayers composed of W/Si, for use in grazing-incidence hard X-ray telescopes, have been shown to operate at energies in excess of 200 keV (J. App. Phys., 2000), and have been successfully deposited onto thermally-formed glass mirror substrates. Other multilayer structures composed of Ni and Ni-alloys are also being investigated (Proc. SPIE, 2000). Multilayers composed of Mo/Si have been developed for mirrors that operate near normal incidence in the soft X-ray band. A complement of six multilayer (Mo/Si) mirrors that operate over the range 17-21 nm have been coated for the TXI solar physics sounding rocket experiment being developed by L. Golub at SAO. Other material combinations for use at much shorter wavelengths are also being investigated. Such coatings could enable the development of diffraction limited X-ray telescopes that operate at 0.3 - 0.5 keV near normal incidence, for milliarcsecond X-ray imaging of stellar coronae, interacting binaries, jets, etc. Such mirrors might ultimately be used for X-ray interferometery with micro-arcsecond resolution.

9. OTHER THEORETICAL INVESTIGATIONS

Jimenez-Garate, together with J. Raymond (CfA), D. Liedahl (LLNL), C. Hailey and B. Goldstein (LLNL), are modelling the X-ray line emission from accretion disks illuminated by a neutron star in low-mass X-ray binaries (LMXB). These computer simulations will allow them to interpret the high-resolution X-ray spectra from XMM-Newton and Chandra telescope observations in terms of a physical picture of the accretion disk, its atmosphere, and corona. They improved upon Raymond's (1993) disk model and use the Hebrew-University/Lawrence-Livermore Atomic Code (HULLAC) to obtain thousands of recombination X-ray lines for the entire disk, also using a new disk-structure code. These lines should be detectable in high-inclination LMXB, when direct emission from the neutron star is obscured in a ''dip.'' They found that low-inclination LMXB do not have easily detectable lines. Evaporating disks have clear spectral signatures (observable in dippers), and a thermal instability occurs in the gas at a critical depth. The disk structure, now including an atmosphere near hydrostatic equilibrium, is more flared than previously thought, and it matches the disk thickness and X-ray albedo calculated using optical light-curve observations (de Jong et. al. 1996). Their model also matched most features from the recently obtained spectrum of the EXO 0748-69 dipper LMXB (Cottam et. al. 2000).

Mori and Hailey have been developing models for improved analysis of isolated neutron stars in anticipation of new Newton and Chandra data. In particular a multi-configurational Hartree-Fock code for arbitrary B-field has been developed which treats higher order Landau levels in perturbation theory. The code is faster than previous codes available to generate relevant matrix elements for neutron star calculations. In addition there are substantial discrepancies with previous work which have been uncovered. This work will be reported in a paper to be submitted this fall as well as at the HEAD meeting in November.

A model for the central engine for cosmic gamma-ray bursts has been developed by Ruderman with Tao and W. Kluzniak (Copernicus Astronomical Center). It is based upon the accretion-induced collapse of magnetized (10^6G) O-Ne-Mg white dwarfs. Such events should result in the

birth of 10^{12} G millisecond-spin-period neutron stars with strong differential rotation: their inner cylinders spin more slowly than their outer ones. Toroidal wind-up of magnetic field by these differently spinning cylinders with radially increasing spin-rates may lead to transient repeated explosive pulsar-like subpulse emission with properties needed for GRB central engines. Development continues on a model for radiopulsar glitches which is not based upon the otherwise needed, but controversial pinning and sudden collective unpinning of quantized vortex lines in the crustal superfluid neutrons. The new model is based upon the interactions between magnetic flux tubes and neutron vortex lines in the stellar core and the pull on the crust of stretched core field which penetrates through it.

Chen and Spiegel have reexamined the evaluation of radiative bulk viscosity (RBV), whose interest stems from conjectures that have been made concerning its possible role in causing an inflationary cosmic expansion. The older methods use an iteration procedure that limits the results to very short mean free paths. When this aspect of the procedure is avoided, and the influence of electron scattering included, a larger RBV than has been found previously is obtained, one that seems to produce a significant inflationary phase in the contexts of both relativistic cosmology and a version of Newtonian cosmology.

Since the approach used in that work involves a modification of the standard asymptotic procedures of kinetic theory, it seemed advisable to seek a check on the method by applying it to classical kinetic theory. Chen, H. Rao (Microelectronics Lab, Columbia) and Spiegel have looked at the derivation of fluid dynamics from the BGK model of kinetic theory, again finessing the iterative procedure that is the hallmark of the Chapman-Enskog method. They obtained fluid equations that are more general than the standard Navier-Stokes equations, but reduce to them in the limit of zero mean free path. The agreement of results of the new equations with experimental findings on shock structure and the propagation of ultrasound is clearly better than for the results obtained from the Chapman-Enskog method and a first account of this has been published.

Together with A. Birch and A. Kosovichev (Stanford), Tao, and Spiegel have studied the instability of magnetoacoustic modes in optically thin radiating atmospheres. They find avoided crossings of modes and are led to suspect that negative energy modes arise in this context. This is aimed to be a case study and it has the advantage of bringing out clearly the nature of the effects of crossings. A paper has been submitted for publication.

Spiegel has continued in his collaboration with S. Talon (Montreal) and F. Paparella (La Jolla) on the study of mixing by overstable convection such as might occur in semiconvection in stars. The oscillatory convection characteristic of this process induces a horizontal shear, as in steady convection, but the combination of this large scale flow with oscillatory convection makes for very effective mixing. An account of this work is in preparation.

Spiegel has been working with C. Pasquero (Turin) and C. Tresser (IBM) on a study of the behavior of a periodically forced nonlinear oscillator (the Duffing problem). The question studied is the fate of the gluing bifurcation of the unforced system when a parameter is slowly varied. The system finds a way around the periodicity constraint by a period-doubling scenario. A publication is being prepared.

Fujita, MacLow, A. Meiksin (Edinburgh) and A. Ferrara (Arcetri) have modeled the effects of repeated supernova explosions in high-redshift dwarf galaxies. They use ZEUS-3D, a second-order, Eulerian, astrophysical gas dynamics code. The goal is to study the role of cosmological feedback in galaxy formation and in metal enrichment of the IGM. A publication is in preparation on parameterizing the rates of mass loss, energy output and metal ejection from starbursts using the local models. These parameters will then be incorporated into a cosmological simulation, using a n-body/SPH code, GADGET, with GRAPE6.

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