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This report covers the period September 1996 through August 1997 and comprises an account of astronomical and astrophysical research carried out in the Department of Astronomy and the Department of Physics.

During the year, Columbia became a member of the MDM Consortium, which operates 1.3 and 2.4m telescopes on Kitt Peak in Arizona, providing substantial new observational capabilities for the Department.

Faculty and Research Associates were James Applegate, Elena Aprile, Norman Baker, Kaiyou Chen, William Craig, Arlin Crotts, Isadore Epstein (Emeritus), Karl-Ludwig Giboni, Charles Hailey, Jules Halpern, David Helfand, Philip Kaaret, Stephen Kahn, Marc Kamionkowski, Laura Kay (Barnard), Lloyd Motz (Emeritus), Robert Novick (Emeritus), Frederik Paerels, Joseph Patterson, Kevin Prendergast, Andrew Rasmussen, R. Michael Rich, Malvin Ruderman, Daniel Savin, Edward Spiegel, Marco Tavani, Wilhelmus van der Veen, and Jacqueline van Gorkom.

Graduate students participating in research were Elizabeth Blanton, Ari Buchalter, Alex Casti, Andrew Chen, Xuelei Chen, Xinzhong Chen, Jean Cottam, Catherine Cress, Deepa Majmudar, Eric Ford, Karl Forster, Akimi Fujita, Mario Jimenez-Garate, Himel Ghosh, Ming Feng Gu, Ilana Harrus, JaeSub Hong, Justin Howell, John Keck, Tomotake Kozu, Kaya Mori, Ravi Pilla, Alex Refregier, David Schiminovich, Adrianne Slyz, Edgar Smith, Joshua Spodek, Ben Sugerman, Gino Thomas, John Tomsick, Robert Uglesich, Matt Umurhan, Leven Wadley, Frank Wang, Fang Xu, and Tianhua Zhu.

Undergraduates participating in research were Ian Adler, Tracy Allen, Kerry Billings, Scott Brown, Rano Chaterjee, Elliott Eggleton, Justin Detray, Amy Jewel, Ali Kinkhabwala, Amina Kinkhabwala, Jonathan Kemp, Miriam Krauss, Sabine Lammers, Michael Malm, Andreea Petric (Barnard), Scott Schnee, Charles Silver, Chelsea Wald and Beth Willman.

High school teachers participating in research were Rachel Berger, Emily James and Britt Reichborn-Kjennerud.

Andrew Chen, Ilana Harrus, Ravi Pilla, Alexandre Refregier, Gino Thomas and Tianhua Zhu received Ph.D. degrees.

Appointments during 1996–97 were held by Adjunct Professor Michael Allison, Postdoctoral Research Scientists Kaiyou Chen, Valeri Egorov, Nobumichi Ishida, Karen Leighly, Frank Summers, Louis Tao, Monica Vallluri, and Ming Zhao.

In July Helfand stepped down as Chair of the department after a reign of more than a decade, van Gorkom was appointed as the new chair. Kahn continued as Director of the Columbia Astrophysics Laboratory.

1. STARS & STELLAR EVOLUTION

Applegate and Thomas have developed a stellar evolution code and used it to follow the evolution of cataclysmic variables to just past the minimum period. The code includes a full treatment of the burning of ^{3}He, necessary to treat the breakdown of nuclear quasi-equilibrium, a self-consistent treatment of mass transfer in Roche geometry driven by angular momentum loss due to gravitational radiation and magnetic winds, and up to date microphysics. They find, that the hypothesis, that gravitational radiation is the only torque acting on the system, leads to the prediction, that the minimum period is 65 minutes instead of the observed 81 minutes. They conclude that magnetic breaking is still operative near the minimum period, and find that they can reproduce the observed minimum period with a total torque of 2.5 times that due to gravitational radiation. Applegate and Thomas also find that the breakdown of nuclear quasi-equilibrium and the mixing of ^{3}He accompanying the disappearance of the radiative core of the donor are not responsible for the 2–3 hour period gap. They find that a drop in the magnitude of the magnetic spindown torque by about a factor of ten at the disappearance of the radiative core gives both the loss of contact at 3 hours and the reestablishment of contact at 2 hours. This work was the Ph.D. thesis work of Eugene R. Thomas.

Applegate and Thomas are incorporating tidal heating and irradiation-driven winds into their code in order to study the transition from Low-Mass X-ray Binary to Black Widow pulsar to isolated millisecond pulsar or millisecond pulsar with planets.

Applegate and Majmudar have analyzed a model in which beryllium and boron are produced in unmixed supernova ejecta by spallation reactions caused by energetic particles accelerated in the ejecta itself. This scenario naturally explains the constant ratio of spallation products to iron seen in low metallicity stars. They find that the correct spallation to iron ratio can be produced if roughly 0.1% of the supernova energy goes into accelerating particles.

During 1996-7 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. We typically observe a star steadily for a few months, trying to amass the densest possible coverage by stressing long observation and distribution of observers in longitude. This provides a time series well suited to the study of periodic signals, and immunized from the ‘‘aliasing’’ problems inherent in data from a single site. The principal observers are in Belgium, Denmark, Maryland, Arizona, Illinois, New Zealand, and Australia. Occasional contributions also arrive from Russia, South Africa, Israel, Japan, and Chile. A grant from the Research Corporation enabled us to make this expansion in the scale of activity. Patterson and Kemp spent most of their time on this enterprise. Most programs involve the study of cataclysmic binaries, justly famous for the many periods frequently present in the light curve.

Perhaps the most interesting result came from intense coverage of CR Boo, a well-known CV with a spectrum dominated by helium. In brief, we found that CR Boo appears to be an essentially garden-variety dwarf nova, despite its exotica (ultrashort period, helium composition). The outbursts occur very often, about every 19 hr, which is why the pattern wasn't noticed before (because this is close to the traditional 24 hr sampling rate). We also found ''superhumps'' in the light curve during the star's bright state, and stabilization of the superhump period after about 3000 cycles. This may well be the characteristic timescale at which normal dwarf nova superhumps mutate into ''permanent'' superhumps.

The classical nova V603 Aql has been an old favorite, and we published a new study of its superhumps. During 1994, the star flashed one signal with a period slightly exceeding $P_{\rm orb}$, and another with a period slightly less than $P_{\rm orb}$. We call these respectively positive and negative superhumps. We interpret them as arising from two types of precessional motion of the accretion disk: the prograde advance of the line of apsides, and the retrograde wobble of the line of nodes.

Large data sets, comprising typically $\sim$200 hr over $\sim$50 nights, have been collected on many other short-period CVs, with the purpose of studying these precessional effects in disks. The most useful results come from the study of permanent superhumps in novalike variables. Essentially all novalike variables with $P_{\rm orb}<3.5$ hr show superhumps. Their study and understanding will keep the group busy for years to come.

Rich, as part of a team of astronomers participating in Hubble Space Telescope globular cluster studies with S. Djorgovski (Caltech), discovered extreme blue horizontal branches in two metal rich globular clusters. There is a primary strong correlation between horizontal branch type and metallicity in that blue HBs are found in metal poor globular clusters, while metal rich globular clusters have red HBs. It has also been suspected that blue HBs are primarily found in clusters with high density cores, but the correlations are not secure. Of 7 clusters with [Fe/H] >-0.5 observed by HST, only NGC 6388 and 6441 have even a small number of blue HB stars. All 7 clusters have blue stragglers. NGC 6388 and 6441 both have $\mu_{V,0}=13.5$ mag/sq. arcsec, the highest central surface brightness of any Galactic globular cluster. While stellar interactions at high density remains an attractive hypothesis, the sudden onset of this phenomenon is not understood, nor is there a clear theoretical explanation. Other possibilities, such as high primordial He abundance, are being considered to explain this result.

Rich has been selected to join the Ad Hoc Science Working Group for the proposed Next Generation Space Telescope mission. Rich has argued that NGST must achieve diffraction-limited spatial resolution for its 8m aperture at 0.5 microns. Rich has stressed the value of measuring ages and star formation histories for stars in nearby galaxies using NGST, to constrain galaxy formation histories from the local fossil record. Such investigations will not only require high resolution, but also need optics to suppress diffracted and scattered light from the (likely) irregularly shaped primary mirror, in order to allow faint object photometry.

Rich, in collaboration with S. Castro and B. Barbuy (U. of Sao Paulo) has analyzed spectra of metal rich dwarfs in the Solar Neighborhood to test whether these metal rich stars originated in the Galactic bulge (on eccentric orbits) or formed in the disk. Stars as metal rich as [Fe/H] $=+0.5$ are found, exceeding the most metal rich bulge giant analyzed. However, [O/Fe] declines as a function of [Fe/H], reaching subsolar values at high metallicity. The alpha-capture elements are not enhanced as they are in the bulge. The most striking difference is that s-process elements are down by 1 dex in these stars, while they are Solar in the bulge giants. There is as yet no explanation for these results.

Rich, in a collaboration led by D. Figer (UCLA) and including M. Morris, I. McClean (UCLA) and G. Serabyn (Caltech), has begun a program using HST and the newly installed NICMOS to image the Galactic Center population in the near-infrared from space. The primary goals of this program are to (1) investigate young star clusters near the Galactic center and (2) to measure the age of the r^{-2} spheroid star cluster at the Galactic center – the stellar nucleus. An early result of this work was the imaging of the ''pistol'' nebula and the ultra-luminous Wolf-Rayet star powering it. The Pistol Star is among the most luminous, if not the most luminous, star in the Milky Way: models place it at $\approx 5\times10^6 L_\odot$. Current imaging cannot rule out the possibility that this is 2 or more stars within a few AU of each other, but even that possibility is very interesting. Only a decade ago, the presence of widespread star formation in the Galactic Center was considered unlikely.

In collaboration with M. Shara and M. Fall (STScI) Rich is analysing HST images of 45 star clusters in the Magellanic Clouds. NGC 121 is among the oldest, most populous, and most compact. The color-magnitude diagram of NGC 121 confirms an age of 12 Gyr from ground-based imaging, but reveals a small population of blue stragglers in the core. This is the first extragalactic detection of blue stragglers in a globular cluster.

Smith, Rich, and Neill have been imaging globular clusters. Fornax globular cluster 3 has been claimed to have an abundance spread due to apparently wide principle sequences. They used CTIO 4m data to carefully subtract field stars from the principle sequences and to do an error analysis which demonstrated that there is no abundance spread in the cluster. Considering all of the Fornax globular clusters in the horizontal branch type vs. metallicity diagram, they point out that the clusters are anomalous compared to the Milky Way clusters. Even after correction for field contamination, these clusters have the reddest horizontal branches at [Fe/H] $=-2$ of any known globular clusters. The presence of RR Lyraes and, in the case of Clusters 3 and 1, carbon stars, strongly indicates that these clusters must be a few Gyr younger than M92, similar to IC 4499. This is in sharp contrast to the globular cluster members of the Sgr dwarf galaxy, which have blue HB's and are consistent (except for Ter 7) with being as old as the oldest globular clusters in the Milky Way. The Fornax and Sgr dwarf galaxy globular cluster systems occupy extreme opposite regions of the HB type-metallicity diagram.

Uglesich, van der Veen and Crotts have used the Starfire Optical Range 1.5m Adaptive Optics telescope and a coro nagraph to obtain near-infrared photometry of the binary containing the very low mass star Gliese 105C. The J, H & K band measurements are consistent with results for the young brown dwarf candidates Calar 3 and Teide 1, and, using an empirical mass-luminosity relationship for low mass stars in the solar neighborhood, a mass of 0.065 $M_\odot$ is estimated for Gl 105C. These conclusions, however, are inconsistent with age estimates of the system based on the chromospheric activity of the main-sequence companion and suggest that care should be taken when identifying brown dwarf candidates based on broad band photometry alone. Regardless of its exact classification, Gl 105C provides a rare opportunity to study the physical properties of an object near the stellar-substellar boundary.

Van der Veen in collaboration with P. Huggins (NYU) and H. Matthews (JAC) have analyzed JCMT observations of neutral atomic carbon in the circumstellar envelopes of eleven evolved late-type stars. CI emission is detected in the envelopes of α Ori and IRC+10216, but is not detected in other envelopes. The detections are in good agreement with previous CI observations indicating that CI is not present in the inner envelope of IRC+10216 (with a CI/CO abundance ratio of $\leqslant 0.01$) but is present in a shell structure of radius 14″, whereas in α Ori CI is the main carrier of carbon in the inner envelope, with CI/CO ≈ 5. The absence of CI emission from the other stars places upper limits on CI/CO in the bulk of their envelopes of $\leqslant 1$ in most cases. The extreme case of α Ori can be ascribed to its supergiant status and the presence of a chromosphere.

Van der Veen in collaboration with Groenewegen (MPE Munich) and Matthews (JAC) used newly obtained JCMT observations of the ^{12}CO and ^{13}CO J = 6-5 lines to construct a model of the circumstellar CO envelope around the nearby carbon star IRC+10216. A spherically symmetric radiative transfer code is used to model these new data in combination with lower transition data from the literature. We find a good fit to the emission coming from the inner part of the envelope but these best fitting models do not fit the extended emission seen in the mapping data. To fit the data for off-sets $>50''$ we need models where the mass loss rate is a factor of five higher in the outer envelope.

Van der Veen in collaboration with several European investigators are currently reducing and analyzing 90 and 160 μm images of seven evolved mass losing stars obtained with the ISOPHOT instrument aboard the ISO satellite. The images are roughly 15×35 arcmin in size and show the distribution of dust as lit up by the central mass losing stars. The goal is to convert the dust distribution as function of angular distance to the star into a mass loss rate as function of time. Depending on the extent of the observable emission this will yield the mass loss history over the last several ten thousand to hundred thousand year. So far twelve out of fourteen scheduled ISO observations have been carried.

Van der Veen in collaboration with M. Groenewegen, A. Omont (IAP, Paris) and B. Lefloch (IRAM) used the IRAM 30m telescope (Pico Veleta, Spain) to obtained maps of the 1.3mm continuum emission from seven evolved mass losing stars. The maps are about 1 arcmin square in size and are obtained with a 11″ FWHM beam. These data enable us to study the most recent mass loss history (last several thousand years) with a time resolution of a few hundred years. Most of this data has been obtained in the spring of 1997 are are now being reduced and analyzed. Data of the nearby mass losing carbon star IRC+10216, which was obtained in the spring of 1996, has already been analyzed in detail and evidence for two phases of enhanced mass loss occurring during the last 2,000 yr were found, each lasting respectively 250 and 600 yr and separated by about 700 yr (Groenewegen *et al.*, 1997, A&A 322, L22).

2. RADIO SOURCES

Helfand, along with his collaborators R.H. Becker (UC Davis) and R.L. White (STScI) continued collecting Faint Images of the Radio Sky at Twenty-cm for their *FIRST* VLA sky survey. As of June, observations covering a total of 5000 deg^2 had been collected, including a $\sim$4300 deg^2 contiguous region in the North Galactic Cap and two smaller strips in the opposite hemisphere centered at $\delta = 0$ deg and $\delta = -10$ deg. Over 34,000 two-million pixel maps have been analyzed, yielding a catalog of $\sim$450,000 radio sources to the flux density threshold of 1.0 mJy. All sources have positions accurate to better than 1″, and $\sim$75,000 have been identified with objects on the POSS plates. The data are all publicly available at the *FIRST* Website: http://sundog.stsci.edu/. A wide variety of followup programs and science analysis projects using the survey are in progress. Briefly, these include:

Helfand and the *FIRST* team continue to pursue the *FIRST* Bright Quasar Survey (FBQS). Spectroscopic identifications are obtained for all stellar objects brighter than POSS I E magnitude 17.5 with colors bluer that $(O-E) = 2.0$ that are coincident to within 1.2″ of a *FIRST* radio source. A total of 1043 spectra have been obtained to date, yielding the detection of over 500 new quasars and BL Lac objects in the first 3000 deg^2 of the survey. These have included remarkably luminous objects (such as a source with $R = 16.$ and $z = 3.4$), the first radio-loud Broad Absorption Line quasars, and a high incidence of gravitational lenses. Projects are underway to extend the survey to redder objects and fainter magnitudes.

Helfand and Willman along with their *FIRST* team collaborators have obtained photometry on over 200 new quasars from the FBQS, providing a large sample for long-term variability studies. They find that nearly 30% have varied by half a magnitude or more, with a marked bias toward fading (rather than brightening) owing to Malmquist bias. The overall distribution of magnitude changes can be fitted with a power law distribution of variability indices.

Helfand, the *FIRST* team, and P. Schechter (MIT) obtained images of 173 of the FBQS sources with $z > 0.9$ and found two gravitational lens candidates, a lensing rate approximately twenty times that of other lens surveys. The first object is a pair of images separated by 1.1″ in both the radio and optical bands, and has been spectroscopically confirmed as a lens. The colors of the third image in the optical data are apparently inconsistent with any plausible lensing galaxy; a

NICMOS observation has been proposed. In addition, Buchalter, in collaboration with J. Lehar (CfA) has constructed a list of candidate lensed radio lobes from the *FIRST* survey, and is following them up with the VLA and MERLIN interferometers.

Helfand and Schnee along with their *FIRST* team collaborators have conducted the *FIRST* unbiased survey of stellar radio emission at sub-millijansky levels. They have matched the Hipparcos and Tycho catalogs to *FIRST*, discovering two dozen identifications, fewer than one-third of which had been previously noted as stellar radio emitters. Using the multiple observations available as a consequence of the substantial overlap of the *FIRST* pointing grid, they show that the majority of these matches are variable, thus supporting the associations. Adding other star catalogs, they show that *FIRST* will more than triple the number of known radio stars and, for the first time, provide a radio star sample unbiased by optical selection criteria.

Blanton and Helfand, along with members of the *FIRST* team, continue to use bent-double radio sources as tracers of the high-density Universe. Keck II multislit spectroscopy carried out in ten bent-double fields shows that all ten contain clusters or groups of galaxies associated with the radio source host galaxy at redshifts ranging from 0.35 to 0.85. Redshifts for several dozen clusters at lower redshifts have also been obtained. They are now constructing a complete sample of bent-double clusters for use in followup X-ray programs and evolution studies. In support of this effort, Fujita has shown that Fanaroff-Riley class I bent doubles are typically found in richer optical fields than FR II sources, whereas there is no such distinction between the two classes for sources which show no evidence of interaction with the intracluster medium.

Blanton and Helfand have also found that a number of bent double fields contain no optical objects down to $R=22$ to 23. They have imaged six of these fields in the near infrared and find, in two cases, rich clusters of objects at 2 microns with $R-K\sim 5$; spectroscopic followup of these objects is pending.

Buchalter, Helfand, and the *FIRST* team have used a sample of over 100 FR II radio quasars from the *FIRST* survey to show for the first time the expected minimum in the angular diameter-redshift relation resulting from the curvature of spacetime. They have explored in detail the various selection effects which have compromised previous samples, and quantify evolutionary effects which limit the accuracy with which cosmological parameters can be derived from such measurements. They conclude that a sample of 500–1000 FR II quasars, obtainable from the *FIRST* database, could set meaningful constraints on q_0.

Cress and Kamionkowski worked out predictions for angular clustering of radio sources in various cosmological models to compare with the correlation function measured for the *FIRST* survey. Radio sources are typically at redshifts of order unity. By comparing with clustering of sources at lower redshifts, one can investigate the evolution of the matter distributin in the Universe and test various models of the origin of structure.

Refregier, Cress, Brown, Helfand, and Kamionkowski (with A. Babul of NYU) have been looking for correlations between ellipticities of sources in the *FIRST* survey which would have been induced by weak gravitational lensing due to inhomogeneities in the mass distribution in the Universe. Much progres has been made in understanding systematic effects in the *FIRST* survey which would mimic such a signal. Predictions for the amplitude of this correlation in various models of structure formation have also been performed. With hundreds of thousands of resolved sources (mostly at large redshift) over a good fraction of the sky, *FIRST* provides a unique probe of this effect over angular separations of a few degrees. It should also be noted that this probes the *mass*, as opposed to luminous-matter, distribution in the Universe.

Buchalter and Kamionkowski are using a k-space analog to the method of Limber's equation to compute a theoretical estimate for the area-averaged skewness (related to the angular 3-point correlation function) of counts-in-cells, arising from an initially Gaussian distribution of density perturbations. This result will be compared to the actual value to be measured from the *FIRST* survey. A comparison of these quantities can yield constraints of the shape of the power spectrum at different angular scales, the redshift distribution of the sources in the survey, and in particular on the linear and first non-linear bias parameters, and thus indirectly on Ω_0.

3. X-RAY & Γ-RAY SOURCES

Aprile, Xu and Mukherjee, with Digel (NASA/GSFC) are studying the high energy diffuse γ-ray emission from the interstellar gas in Orion, using observations from the *EGRET* instrument on *CGRO* and radio surveys of the H_1 and CO emission. They are completing the analysis of data from all viewing periods of the Orion cloud region to determine the molecular mass calibrating ratio $X=N(H_2)/W_{\rm CO}$ and the γ-ray emissivity per nucleon in the ISM, with better precision allowed by the increased exposure. Possible energy dependence and spatial variations of these quantities, as well as significant excesses due to point sources are looked for.

Craig and Hailey have analyzed *ROSAT* data on several sources. They have completed a more detailed study of the X-ray Emission from the SNR CTB1, and have as yet unpublished radio observations on this source. They are also analyzing new *ROSAT* HRI observations of a possible isolated thermally emitting neutron star (RXJ0002). A large scale search of the *ROSAT* database of pointed observations is also underway to identify more candidate isolated, thermally emitting neutron stars for potential followup with AXAF.

Halpern is obtaining optical identifications of flat-spectrum radio sources that have been proposed as blazar counterparts to unidentified EGRET sources. Optical counterparts of approximately nine radio sources have been found so far, and five optical spectra have been obtained by Halpern, Eracleous, and Blundell (Oxford), yielding either redshifts or featureless continuum. These will be used to improve the identification statistics of γ-ray blazars, to study the lower limits of radio power among them, and to evaluate

the need to postulate an additional class of high-energy γ-ray source. At low Galactic latitude, the identity of majority of the EGRET sources is a continuing mystery. Halpern and Helfand are attempting to identify several EGRET sources at low to intermediate Galactic latitude by covering their error circles with *ROSAT* HRI and VLA pointings. If these sources are pulsars, then they might have faint X-ray counterparts and/or steep-spectrum radio counterparts in blank optical fields. However, they may also represent a new class of Galactic object, or perhaps blazars that are relatively radio quiet, in which case they could also be indentified using this multiwavelength approach. X-ray observations of three EGRET field have been obtained, and the optical identifications of the detected sources are almost complete. At least one possibly interesting identification is being pursued. Two more EGRET fields remain to be observed by *ROSAT*. Halpern is also examining the brightest unidentified high-latitude source 2EG 1835+5919 through optical imaging of its entire EGRET error circle at the MDM Observatory. Complementary X-ray observations of this source have been proposed.

Helfand and E. Moran (Berkeley) have completed a study of the starburst galaxy NGC 3256 at X-ray wavelengths. They demonstrate that X-rays arise in three distinct components: from an outflowing galactic wind, from the galactic disk, and from the nuclear region. The latter source has a hard X-ray spectrum, and they show that it is likely that this component arises from inverse compton scattering of the copious infrared photons off the relativistic electrons created by supernovae in the starburst region. This result has significant implications for the contribution of starburst galaxies to the cosmic X-ray background.

Helfand and E. Moran also completed the analysis of the *ASCA* spectrum of the most luminous, high-redshift X-ray quasar, 1508+5714, discovered in their earlier Einstein two-sigma survey. X-rays are detected over the entire rest-frame energy range from 3 to 53 keV, and are well-fitted by a single power law spectrum with an energy index of 1.4. Evidence that a beamed component contributes significantly to the flux from this source is adduced from X-ray and radio variability data. These results support the notion that the X-ray spectra of such objects show no evolution with redshift.

Helfand and Chatterjee have been studying a deep *ROSAT* HRI observation of the radio pulsar PSR1929+10 which turns out to be the deepest high resolution X-ray image ever taken in the Galactic plane. The high column density through the Galaxy at this low latitude ($b = 3$ deg) obscures the emission from background AGN, allowing a census of faint X-ray emitting stars which constrains their contribution to the Galactic X-ray background.

Helfand, in collaboration with T. Lozinskya (Moscow) have completed a study of the X-ray image of the Local Group dwarf galaxy IC1613. They confirm the speculation by Eskridge that the dominant X-ray source in this field is a background galaxy cluster, but discover that the only known supernova remnant in the galaxy is also a lumnious X-ray source. VLA data, along with extensive spatially resolved spectroscopy obtained with the Russian 6-m telescope, reveal a picture of a luminous middle-aged remnant similar in nature to the brightest optical SNR in the LMC, N49.

Helfand, B. Oppenheimer (Caltech), and E. Gaidos (MIT) completed their search for sources of extended X-ray emission in the *Einstein* Observatory database. They found a total of 321 unidentified extended sources at high Galactic latitude, many of which may be uncatalogued galaxy clusters and groups at moderate redshifts.

Kaaret, Ford, and Chen have shown that the behavior of the high frequency QPOs from two X-ray binaries may be evidence for strong-field general relativity. The key point is that general relativity allows no stable orbits for massive particles within 3 Schwarzschild radii of a massive compact object (the radius of instability moves inward if the object is rotating). Two high-frequency QPO sources exhibit QPOs with little or no dependence of QPO frequency on source intensity. The QPO frequency appears to wander randomly, covering a range on order of 50 Hz on a time scale of order 1000 s. This behavior is consistent with that expected if the accretion disk is disrupted at the radius of the marginally stable orbit. Our result is very exciting as it is the first direct observational signature of the existence of the marginally stable orbit. Our result implies that high-frequency QPOs in X-ray binaries provide a means to measure the masses of neutron stars in X-ray binaries and to probe the strong-field regime of general relativity.

Kaaret, Ford, and Tavani with B.A. Harmon (NASA/MSFC), S.N. Zhang (USRA), J. Grindlay and P. Bloser (CfA), and D. Barret (CESR) have continued a study of the fast quasiperiodic oscillations (QPOs) at frequencies near 1 kHz from the X-ray burster 4U 0614+091. They found that the QPO frequency is well correlated with the flux of a blackbody component of the X-ray emission. Kaaret and Ford have interpreted additional correlation between the spectra and fast timing properties of this source as evidence that the soft blackbody emission originates in the accretion disk. This identification may lead to constraints on the radius of the neutron star in 4U 0614+091 and other similar low-mass X-ray binaries.

Kaaret and Chen have completed their study of the diffuse high-energy γ-ray background. Their analysis has led to the first direct measurement of the inverse-Compton production of γ-rays in the Galactic halo. They have shown that the properties of the isotropic background are consistent with an origin in emission from unresolved γ-ray AGN and have placed constraints on the number versus flux relation for γ-ray AGN.

Kaaret and Tomsick are analyzing observations of black hole candidate X-ray binaries made with *RXTE*. They have analyzed data from the recurring X-ray transient 4U 1630-47 and found a dip in X-ray lightcurve do to an absorption event. The spectral evolution during the dip allows them to constrain the size of the hard X-ray emitting region. They are currently analyzing joint *RXTE* and *OSSE* spectra of the superluminal jet source GRO J1655-40.

Pilla has completed the work he had begun with the late Jacob Shaham on the kinetics of relativistic electron-positron pair plasmas. He is presently collaborating with A. Loeb (Harvard) on the problem of computing the emission spectra from relativistic-shock models for cosmological gamma-ray bursts. Under the supervision of Ruderman he has completed

his Ph.D. dissertation on the ''Fireball Sources of Cosmological Gamma-Ray Bursts.''

Tavani was engaged in theoretical and interpretative work regarding high-energy astrophysical sources, including γ-ray bursts, observations and theory of γ-ray transient sources near the Galactic plane, interpretation of X-ray/radio data of galactic superluminal X-ray sources, theory and observations of X-ray bursters and soft X-ray transients such as Aquila X-1.

Tavani has been involved in several studies of γ-ray burst (GRB) phenomena. Recent detections of GRB X-ray afterglows by the *BSAX* and *RXTE* satellites opened a new field of GRB research. Rapid follow-up observations in radio and optical bands are now possible for the GRBs identified in the X-ray range with a relatively small error box. Tavani participated in several *BSAX* investigations and is involved in theoretical analyses of *GRO*, X-ray satellite and HST data. Immediately after the discovery of the first GRB X-ray afterglow for GRB 970228 and its associated optical transient (OT) Tavani showed that cosmological and Galactic models of delayed emission can be strongly constrained from BSAX observations. He showed that adiabatic relativistic fireballs involving reverse shocks are not compatible with the observed temporal behavior of the GRB 970228 X-ray afterglow, and calculated the required particle energy acceleration properties for forward shocks. If X-ray (and optical) afterglows are a consequence of efficient particle energization by a shock wave in a dilute medium, the temporal characteristics of the emission detected by *BSAX*, *ASCA* and *ROSAT* in the case of GRB 970228 strongly constrain the acceleration properties of relativistic particles. Tavani also shows that simple cooling of a neutron star surface is not compatible with the combined X-ray observations of GRB 970228. Tavani is currently developing a hydrodynamical and radiative model of GRB afterglow emission that includes acceleration and cooling processes. Bright GRBs are not necessarily related to detectable X-ray/optical afterglows: only GRBs capable of accelerating long-lived relativistic particle distributions may lead to detectable afterglows.

The shock synchrotron model of GRB emission initially proposed by Tavani in 1995 has been further developed. Tavani shows that the agreement with the spectral results by *GRO* instruments and the theoretical relativistic synchrotron spectrum extends to X-ray energies as confirmed by *BSAX* and *Ginga* results. This model agrees with qualitative expectations of relativistic fireball shock emission. Tavani is involved in a theoretical analysis of time-resolved X-ray/γ-ray spectra of all *BSAX* data in collaboration with E. Costa (IAS, Frascati) and F. Frontera (ITESRE, Bologna). An apparent absorption of low-energy X-rays during the initial part of some GRB pulses is being investigated. Particularly important are optical observations of OTs possibly associated with GRBs. Tavani is carrying out a theoretical analysis of HST observations of GRB 970228 (whose nature is currently controversial) and GRB 970508. If GRB 970508 is associated with the OT at redshift $z \gtrsim 0.8$, the lack of a host galaxy as determined by HST observations indicates for the first time a possible origin of GRB in star forming galaxies. Tavani is currently working on a systematic assessment of the extragalactic model of GRB formation in light of the recent afterglow detections and properties of the $\log N - \log P$ distribution.

Tavani, Halpern, and R. Mukherjee (NASA/GSFC) continued their study of a special class of unidentified γ-ray sources along with D. Thompson, D. Kniffen (NASA/GSFC), and J. Mattox (Boston U.). A comprehensive analysis of *EGRET* data for the unidentified γ-ray source 2CG 135+1 was completed with the discovery of significant variability of the γ-ray flux for both short (weeks) and long (months) timescales. Since no isolated γ-ray pulsars is known to vary (within statistical uncertainties) and from the lack of radio-loud AGNs in the γ-ray error box, it is deduced that 2CG 135+1 belongs to a new class of γ-ray emitters. 2CG 135+1 shares many characteristics together with another remarkable non-blazar γ-ray transient discovered in 1995 by the Columbia group near the Galactic plane, GRO J1838-04: (1) variability of the γ-ray flux within days/weeks, (2) occasional peak γ-ray emission of comparable flux ($\sim 4 \times 10^{-6}$ ph cm^{-2} s^{-1}), (3) absence of radio-loud spectrally-flat AGNs or prominent radio pulsars within their error boxes, (4) lack of strong X-ray and/or hard X-ray counterparts. 2CG 135+1 and GRO J1838-04 provide strong evidence for the existence of a *new* class of variable γ-ray sources. Tavani and collaborators show that, if radio-quiet AGNs produced γ-ray flares comparable to what is observed from 2CG 135+1 and GRO J1838-04, *EGRET* should have detected a much larger population of γ-ray sources. The position of both 2CG 135+1 and GRO J1838-04 near the Galactic plane also reinforces the interpretation in terms of a new class of Galactic variable γ-ray sources.

Tavani and collaborators including J. Paredes (U. of Barcelona) and R. Foster (NRL) show that the γ-ray flux from 2CG 135+1 appears to be anticorrelated with the cyclic radio emission from the radio star LSI 61 303. The observed anticorrelation is similar to what was previously observed in the soft X-ray band by *ROSAT* suggesting a common nonthermal origin. Additional *BSAX* and *XTE* investigations are currently carried out to test whether the behavior of X-ray emission is repetitive. If confirmed, an anticorrelation between γ-ray/X-ray emission from 2CG 135+1 and the radio emission from LSI 61 303 would be of the greatest importance for the interpretation of unidentified sources. Tavani is developing a theoretical model of high-energy and radio emission for an energetic pulsar embedded in a gaseous outflow from a companion star following previous investigations by Tavani and Arons (UC Berkeley) for the PSR B1259-63 system.

In a separate project on low-mass X-ray binaries, Tavani, Kaaret and Ford together with B.A. Harmon, S.N. Zhang (NASA/MSFC), and J. Grindlay and D. Barret (Havard) continued the study of hard X-ray emission from accreting neutron stars. Several new X-ray bursters were detected in the hard X-ray range by *BATSE* during 1996. The total number of accreting neutron stars detected above 20-30 keV is now twelve, as summarized by Tavani and Barret in an invited review for the proceedings of the 4th *Compton* Symposium. A program for target-of-opportunity observations of X-ray bursters during episodes of hard X-ray emission by BSAX

and *RXTE* is under way. The X-ray burster GS 1826-34 was observed by *BSAX* during October 1997 in the framework of this program. Thermal and non-thermal models of hard X-ray emission from accreting neutron stars is being investigated by Tavani and Liang (Rice). Of particular relevance is the discovery by Tavani and collaborators of the BSAX team (L. Stella and S. Campana, Oss. Astron. Rome) of a sudden transition in the X-ray lightcurve of the transient Aquila X-1 (showing coherent QPOs in the 7–800 Hz) following a major outburst in 1997. The residual X-ray emission is particularly hard and suggestive of shock-powered emission as predicted in models of hidden millisecond pulsars developed by Tavani.

Tavani continues his collaboration with *GRO*, *ASCA*, *BSAX* and radio observers for the study of superluminal Galactic X-ray sources, GRS 1915+105 and GRO J1655-40. Tavani leads the steering committee for a NASA program for radio monitoring of high-energy sources at the Green Bank Interferometer. Particularly important is the repeated radio flaring emission detected during 1997 from GRS 1915+105 and correlated with soft and hard X-ray outburst emission as detected by *RXTE-ASM* and *BATSE*. A recent *ASCA* observation of GSR 1915+105 shows the existence of variable spectral features whose nature in under investigation. Tavani is developing a model of magnetic field instability in accretion disks which can be used for the interpretation of these data.

4. PULSARS & NEUTRON STARS

Halpern and Wang are studying rotation-powered pulsars with *ASCA* and *ROSAT*, and are proposing together with G. Pavlov (Penn State U.) for longer observations of several of these to study phenomena such as the spectrum of a neutron star atmosphere, and the spectrum and pulse profile of a millisecond pulsar. These new observations are necessary to disentangle thermal and nonthermal processes that may be present in the same object, and to correctly derive quantities such as the effective temperature of the neutron star surface, the luminosity of a heated polar cap, and the M/R relation of the neutron star. Recent results include the detection of pulsed hard X-rays from the polar caps of the older pulsars B1929+10 and B0950+08 in *ASCA* observations, and confirmation of X-ray emission from the millisecond pulsar J1012+5307 using the *ROSAT* HRI. A long followup *ROSAT* observation of the latter is planned in order to determine whether its X-rays are thermal from heated polar caps, or nonthermal magnetospheric emission.

Wang, Ruderman, Halpern, and Zhu have developed a general model for X-ray emission from rotation-powered pulsars that explains both the hard X-ray power law which is seen in strong γ-ray pulsars, and the weakness of thermal polar cap emission in those objects. In this picture, >100 MeV γ-rays convert into $e^{\pm}$ pairs on closed field lines where $B \sim 10^{10}$ G. The synchrotron radiation of those pairs is responsible for power-law emission with energy index 0.5. The pairs themselves form an optically thick cyclotron resonance blanket which reflects hot polar cap X-rays back to the surface of the neutron star, where they are reemitted at a lower temperature.

Ruderman, Zhu, and K. Chen continued work on the physics of neutron star flux tube movement induced by stellar spin-down or spin-up. Consquences of the induced crustal motion together with the magnetic field imbedded in it lead to a model for the spin-down indices of very young pulsars and to an explanation of the very different values for them in the Vela pulsar and in older ones.Among those features of pulsar timing glitches which seem well fit by the model are glitch activity, permanent shifts in spin-down rates after glitches in young pulsars, the intervals between glitches, families of glitches with different magnitudes in the same pulsar and a sharp drop in glitch intervals and magnitudes when spin-periods approach about one second.

Chen, Ruderman and Zhu have applied the model to spun-up millisecond pulsars. They show why this should result in a very high fraction of the most rapidly spinning ones being aligned with a pulse width of almost the full pulsar period and a similarly high fraction being orthogonal rotators. Special application of the model was made to PSR J0437-4715.

W. Kluzniak (Wisconsin) and M. Ruderman are developing a model for cosmological Gamma-ray Burst sources based upon newly formed millisecond period pulsars which have large internal differential rotation.

5. GALAXIES

Buchalter and Kamionkowski investigated how one might learn more about the nature of the objects responsible for gravitational-microlensing events observed toward the Galactic bulge. They investigated the prospects for regular observation of the small distortion to the standard microlensing light curve which arises from the Earth's orbital motion. Detailed and accurate followup observations of lensing events in progress may be able to distinguish such distortions and therefore provide information on the masses, distances, and speeds of the deflectors.

Crotts, Uglesich and Tomaney (U. Washington) continued, in late summer through early winter 1996 and 1997, their survey of microlensing in M31. As well as accumulating more data on candidate events, they have shown that a class of Mira-like variables exist which can masquerade as a microlensing event in sparsely sampled data, requiring them to observe for another season before stating more certainly which candidates are microlensing events. One of their original six events was ruled out on the basis of actually being one of these variables.

The structure of nearby clusters of galaxies and the evolution of their galaxy population is being investigated by van Gorkom. Deep imaging in the neutral hydrogen line is combined with optical photometry and spectroscopy, radio continuum, and, if available, with X-ray imaging. The clusters under study are Coma, Hydra-I and Abell 2670.

With Bravo-Alfaro, Cayatte and Balkowski (all from Meudon) HI images have been obtained of the 25 brightest spirals in Coma. The data show a variety of phenomena: severely stripped spirals very close to the center, moderately gas rich starbursting galaxies at the periphery of the central X-ray source, a lack of HI in the post starburst galaxies, gas rich groups and some interacting and merging galaxies in the

outskirts. These data support our current view of Coma as a rich cluster, which is still accreting groups that fall in along filaments.

Analysis of a complete, volume limited, HI survey of Hydra-I by Valluri and van Gorkom shows that the cluster consists of 3 subclusters seen in projection along the line of sight. The reanalysis of these data solves several puzzles: the lower velocity dispersion of the central subcluster now fits nicely onto the X-ray luminosity-velocity dispersion relation. Also, the hydrogen deficiency in the central cluster is about average, while the fore and background group have no significant HI deficiency.

Abell 2670, a very rich cluster at $z = 0.08$, is being analyzed by van Gorkom, Dwarakanath (RRI, India), Guhathakurta and Shambrook (UCSC) and Poggianti (IoA, Cambridge). Although this cluster used to be a textbook example of a dynamically relaxed cluster, the neutral hydrogen observations (about 40 detections) show clear evidence for dynamically bound groups of spirals currently falling into the cluster. As in Coma the HI detection rate of post star burst galaxies is very low. Again, mergers and interactions occur exclusively in the outskirts of the cluster. All these data indicate that neutral hydrogen is a powerful tool for revealing substructure in clusters.

The HI environment of nearby Ly α absorbers is being investigated by van Gorkom, Lee, Billings, Carilli (NRAO), Stocke and Shull (Univ. of Colorado). A complete data set, in which a fixed volume around each absorber is searched down to the same sensitivity is still being analyzed. More evidence has been found for small, gas-rich galaxies at large projected distances, but close in velocity, to the Ly α absorber. One exciting result is the discovery of six Ly α absorbers arising in a group of galaxies.

As part of an ongoing study of the advanced stages of merger remnants multi configuration VLA HI studies have been made of two selected shell ellipticals. NGC 3656 was observed by Balcells (IAC, Tenerife), van Gorkom and Sancisi (Kapteyn Institute, Groningen). The results are reminiscent of what is seen in NGC 5128 and provide yet more evidence that gas rich shells may result from major mergers. NGC 1210 is being analyzed by Petric (Barnard), Schiminovich, van Gorkom and van der Hulst (Kapteyn Institute). The huge HI mass of this galaxy suggests that this system also results from a major merger, the morphology of the shells indicates that multiple events may have occurred and provide an ideal test bed for comparison with simulations.

A kinematical analysis of four giant low surface brightness galaxies by Pickering and Impey (Univ. of Arizona), van Gorkom and Bothun (Univ. of Oregon) shows that these galaxies are dark matter dominated at all radii. The lack of star formation even at surface densities above the critical threshold suggest that the velocity dispersion may be greater than 10 km/s in these galaxies.

6. ACTIVE GALACTIC NUCLEI

Forster is studying *ROSAT* and *ASCA* observations of intermediate-type Seyfert galaxies for their variability, spectra, and spatial distribution of soft X-rays. These data will be used to address unifying schemes for Seyfert galaxy classification, the relationship between AGNs, normal and starburst galaxies, and the sources of the X-ray background.

Halpern and Eracleous (UC Berkeley) are continuing their long-term spectroscopic monitoring of very broad, double-peaked Balmer lines, which are found preferentially in radio-loud AGNs. The main source of data for this program is the KPNO 2.1m, but telescopes at CTIO and Lick Observatory are also being used. 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. Recent results include the rejection of the binary black hole model in three objects (Arp 102B, 3C 332, 3C 390.3), and the discovery of a 2.2 year transient period in the line profile of Arp 102B, which can be interpreted as the orbit of a hot spot in an accretion disk around a black hole of $2.2 \times 10^8 M_\odot$ (Newman *et al.* 1997). Similar, possibly cyclic behavior in other objects appears to favor dynamical motions in the accretion disk as the cause.

Halpern and Eracleous are also continuing their study of the X-ray spectra of broad-line radio galaxies (BLRGs) with *ASCA*, and comparing their Fe Kα properties with those of ordinary Seyfert galaxies. In general, the Fe Kα line are weaker in the BLRGs than in Seyferts, which may indicate a difference in the structure of the inner disk. In particular, the inner disk in BLRGs may be an ion torus, which would not have a cold target for the production of fluorescent Fe emission.

Kay, Eracleous, Halpern, Magalhaes (IAG/USP), and Moran (UC Berkeley) are studying double-peaked broad-line radio galaxies with spectropolarimetry at Lick Observatory and CTIO. Simple predictions of the polarization due to electron scattering atmospheres on disks, while consistent with published data on Arp 102B, do not describe their observations of five additional objects. These show a variety of complex features in the wavelength dependent polarization of their emission lines and continuum, which is interesting behavior that remains to be understood.

Leighly is performing a comprehensive spectral and variability of narrow-line Seyfert 1 galaxies (NLS1s) observed by *ASCA*. During the analysis of observations of about 20 objects, she made two interesting discoveries. In collaboration with R. Mushotzky, K. Nandra (NASA/GSFC) and Forster, she discovered peculiar features around 1 keV in the spectra of three objects. The shape of these features suggested the presence of ionized material in the line of sight to the X-ray source. If so, features from highly ionized oxygen are expected to be present because of it's high abundance and large cross section. However, the energies of the feature were more consistent with highly ionized neon or iron L, but that interpretation required a large iron overabundance was required. They could be attributed to oxygen if they originate in a wind flowing towards us at highly relativistic velocities. When modeled as absorption edges, outflow velocities near 0.2–0.3 c were required, near the limit predicted by ''line-locking'' acceleration mechanisms. If instead interpreted as broad absorption lines, the implied velocities are about 0.57 c, interestingly near the velocity of particles in the last stable orbit around a Kerr black hole, although a physical interpre-

tation of this fact is not obvious. Interpretation in the context of a relativistic wind is supported by the fact that narrow-line Seyfert 1 galaxies share many optical emission-line and broad band properties with low-ionization broad absorption line quasars which recognized by the presence of blue-shifted absorption lines in their UV spectra. Many of these objects show strong or extreme Fe II and weak [O III] mission, have red continuum spectra and relatively strong infrared emission, and finally, both classes are predominately radio quiet.

Leighly also worked on the spectra from individual NLS1s in collaboration with F. Fiore (Rome Astronomical Observatory) and A. Comastri (Bologna Astronomical Observatory). A SAX spectrum from the NLS1 Ton S180 showed an iron line with energy indicating that it emerged from ionized material. This has important implications, since one explanation for the extremely steep X-ray spectrum and typically rapid, high amplitude variability is that these systems are characterized by a high accretion rate near the Eddington limit, and accretion disks around rapidly accreting systems are predicted to be ionized. In the spectra of another NLS1, PG 1244+026, emission features around 1 keV were seen. These were postulated to originate from ionized neon and iron, which may possibly dominate the spectrum when the photoionizing spectrum is extremely soft.

Leighly found evidence for a rest-frame ionized absorber in another NLS1, IRAS 17020+4544. Since it has a reddened optical spectrum, it seemed possible that the ionized absorption in this galaxy could be coincident with dust. Dust causes reddening in the optical spectrum, but it can also cause polarization. With Kay, and B. Wills, D. Wills, and D. Grupe (University of Texas, Austin), imaging and spectropolarimetry were obtained at the Lick and McDonald Observatory, and high polarization was confirmed. To investigate whether ionized absorption in the X-ray spectrum is generally associated with the presense of polarization in the optical spectrum, results from a sample of Seyfert 1 and 1.5 galaxies were compiled. All of the highly polarized Seyferts had warm absorbers in their X-ray spectra. Spectropolarimetry provides information about the geometry of the emission and scattering regions, and the coincidence of dust and the warm absorber constrains the conditions and location of this material. Therefore, this result holds deep implications for the origin, location and physical composition of the scattering, absorbing and emitting material in Seyfert 1 galaxies.

Sako, Liedahl (LLNL), Savin, Kahn and Paerels extended the spectroscopic study of X-ray photoionized plasmas to Seyfert 2 galaxies. The X-ray spectral model for recombination (discrete and continuous) emission from photoionized gas that so successfully accounted for the spectrum of the massive X-ray binary Cygnus X-3 was extended with the emission expected from the Fe L ions (too heavily absorbed in Cygnus X-3 to be observable), as well as fainter transitions (Balmer series) in Hydrogenic and Helium-like Fe and lower Z-ions. The soft X-ray spectra of Seyfert 2 galaxies are dominated by discrete emission, the excitation mechanism of which is a matter of considerable current debate. Emission from shocked, hot gas associated with a starburst, recombination in cool gas photoionized by the strong nuclear continuum source, as well as resonance scattering of continuum photons by a photoionized 'mirror' have all been suggested. They find that in NGC 1068, the soft X-ray brightest Seyfert 2, analysis of the soft X-ray line spectrum as observed with the CCD spectrometers on ASCA alone cannot decide this issue - the energy resolution of a CCD spectrometer is not good enough. All one can say is that a pure recombination spectrum, as well as a pure resonance scattering spectrum are excluded; a pure coronal spectrum implies unreasonable elemental abundances. Higher spectral resolution will be required to address this problem. Interestingly though, a pure recombination spectrum fits the ASCA spectrum from the Seyfert 2 nucleus in the Circinus galaxy remarkably well. In fact, the observed spectrum looks remarkably like the spectrum from the massive wind-accreting binary Vela X-1 in eclipse. In this latter source, an interpretation of the discrete spectrum in terms of emission from X-ray photoionized gas is natural. A quantitative analysis of these two source spectra is currently underway.

7. COSMOLOGY

Crotts, Burles (UCSD) and Tytler (UCSD) showed using Keck HIRES spectra of a very close, moderate redshift (about 2.5) triplet of quasars that heavy element absorption-line systems do not cluster in space i.e. transversely between sightlines, as would be predicted in a simple interpretation of their line-of-sight clustering, as is often used to describe the structure traced by such absorbers. This indicates that a large component of line-of-sight clustering up to velocity splittings of 600 km/s may be due to internal structure of absorbers, and not spatial clustering as has often been assumed.

Crotts and Fang use KPNO 4-meter spectra of a number of quasars in close pairs and groups on the sky to show that strongly-absorbing ($W_o > 0.4$Å) Lyman alpha clouds have a shape more consistent with sheets or spheres rather than filaments, as predicted by some models. They use the same data to show that such Lyman alpha clouds cluster strongly in space, at a detection level which is now unambiguous. They also use these data to test whether ionization of intergalactic neutral hydrogen due to foreground quasars can be found in the spectra of quasars sitting behind them. The resulting measurement does not support a simple interpretation of the ''proximity effect.''

Cress has worked with a group in Cambridge on 'holes' in the Microwave Background that could be the Sunyaev-Zeldovich signature of very distant clusters of galaxies. Ryle Telescope observations are being combined with deep VLA data, where the 'hole' was first noted, to investigate the nature of the feature. The implications for standard cosmological models are also being considered.

Kamionkowski and his collaborators, Kosowsky (Harvard) and Stebbins (Fermilab), investigated what can be learned from the polarization of the cosmic microwave background. They developed a formalism for describing a polarization map of the CMB that allows the density-perturbation and gravitational-wave contributions to the CMB anisotropy to be disentangled a in model-independent way. This will allow a unique and unambiguous reconstruction of primordial density perturbations and will help test structure-

formation theories, especially inflation. Kamionkowski and Kosowsky more recently evaluated the sensitivity of NASA's Microwave Anisotropy Probe (MAP) and ESA's Planck Surveyor to the polarization signature of gravitational waves. Wadley and Kamionkowski are creating simulations of temperature-polarization maps and developing statistical techniques required to measure the temperature-polarization power spectra with CMB maps with incomplete sky coverage, such as those which will be provided by MAP and Planck.

In related work, Kamionkowski and Loeb (Harvard) showed that by measuring the polarization of the CMB toward numerous clusters, the primordial mass distribution could be reconstructed throughout the volume of the observable Universe, rather than just at the surface of last scatter. Although this requires detector sensitivities well below those in current experiments, such a measurement may become feasible with a future generation of CMB experiments.

Xuelei Chen and Kamionkowski and Liddle and Hindmarsh (Sussex) investigated the dynamical stability of a cosmological model with a closed geometry but a matter density less than critical. This model was found to be stable to small density perturbations, but a precise explanation for the rather curious initial conditions remains to be found.

Kamionkowski and collaborators Bergström (Stockholm) and Edsjö (Uppsala) investigated the improvement in the sensitivity of neutrino telescopes to point sources that can be achieved with better angular and energy resolution. Xuelei Chen and Kamionkowski are calculating some cross sections needed for predictions for rates for indirect detection of weakly-interacting massive particles (WIMPs). Kamionkowski and Kinkhabwala have investigated the uncertainties in predicted WIMP detection rates which arise from imprecise knowledge of the spatial and velocity distribution of these particles in the Galactic halo.

Summers worked with collaborators McMillan (Drexel), Hut (IAS), and Makino (Tokyo) on a design study of the next generation of special purpose hardware, known as the GRAPE series, for computing the N-body problem. Their work was part of an NSF funded initiative to look toward petaflops computer performance, the design bottlenecks, and the applications which might make use of them. The GRAPE series of hardware boards was found to be eminently extendable into the 100 Teraflops range, though some I/O bottlenecks need to be solved before petaflops can be reached. The diversity of applications for such a machine was explored in the various areas of astrophysics with broad range of usefulness, though a few target areas would be most benefited. In particular, cosmological simulations would require a highly parallelized machine design to avoid I/O bottlenecks, while studies of globular clusters do not need a high degree of parallelism. The design recommendations from the study proposed several avenues for pursuit, depending upon the target problem and funding size. Of most importance, the study concluded that a petaflops class machine to perform N-body calculations could be built by the year 2000, with approximately $10 million in funding and a 1998 start date.

In support of the above described GRAPE design study, Summers worked with collaborators R. Melhem (Pittsburgh), B. Elmegreen (IBM), and P. Brieu (Meudon) on developing an N-body code suited for the type of massively parallel machine the next generation GRAPE would need for effective cosmological simulations. An adaptation of the P3M gravity code has been written to specifcally utilize the MPI programming interface with the target machine of the IBM SP2. The code has been successfully tested on the SP2 here at Columbia and shows good promise. The adaptation to utilize the GRAPE hardware has been completed, and testing will now progress in collaboration with IBM's T.J. Watson Research Center. Concepts, developments, and plans were presented at an IBM sponsored forum to foster devlopment on a larger project involving the molecular dynamics community as well.

Summers has been carrying out research on structure formation with the aid of large N-body simulations. He and collaborators J. Kepner and D. Spergel (Princeton) have developed a new statistic, the redshift dispersion, which may provide a reliable determination of the mass density of the Universe with future redshift surveys such as the Sloan Digital Sky Survey. The main advantage of this statistic is that it does not require measurements in the highly non-linear regime and therefore should be less dependent on the currently unknown biasing between the galaxy and the mass distributions.

Summers and collaborators J. Dalcanton and D. Spergel (Princeton) have also presented a scenario for the formation of disks which explain the properties of low-surface-brightness galaxies as well as normal galaxies. Their model produces flat rotation curves and exponential surface-brightness profiles and reproduces the Tully-Fisher relation as a function of surface brightness and the observed distribution of scale lengths and surface brightnesses. The luminosities and angular momenta are determined in this model by the initial mass, angular momentum, and baryon fraction of the protogalaxy.

In a continuation of this work, Summers, Kamionkowski, Sugerman, and A. Babul (New York University) are currently investigating the distribution of protogalactic masses and angular momenta in an effort to understand how the luminosity function and angular-momentum distribution of disk galaxies arises from an initial power spectrum of density perturbations. To do so, a large-scale N-body and hydrodynamic simulation has been carried out. Galaxies have been identifed at redshift zero in this simulation and traced back to the protogalaxies from which these galaxies evolved. The distribution of protogalactic masses and spins is being compared with a linear analytic model.

Summers is also working half-time on astronomy outreach at the Hayden Planetarium. His job there is part of the complete rebuilding of the planetarium over the next several years and focuses on the scientific content of the exhibits and planning for the new Sky Theater and the rebirth of the Department of Astrophysics within the American Museum of Natural History. This joint appointment represents a concrete link between research and public outreach.

8. OTHER THEORETICAL INVESTIGATIONS

Kamionkowski has been part of a large collaboration led by Bahcall (IAS) to produce a comprehensive review of the nuclear-reaction rates for stellar-evolution calculations and for solar-neutrino fluxes. Kamionkowski and Bahcall also isolated a flaw in a recent calculation of the cross section for the $pp \rightarrow de^{+}\nu$ reaction that gave divergent results. Xuelei Chen, Kamionkowski, and Bahcall re-calculated the electron-screening correction to nuclear fusion rates in stellar interiors.

Bracco (Istituto di Cosmogeofisica, Turin), Provenzale (Istituto di Cosmogeofisica, Turin), Yecko (F.S.U.) and Spiegel have been studying the fluid dynamics of accretion disks. They have simulated fluid motions in Keplerian shear and find that if the Reynolds number is high and there is background noise, vortices form and last many rotation periods.

Von Hardenberg (Istituto di Cosmogeofisica, Turin), Paparella (Istituto di Cosmogeofisica, Turin), Platt (I.D. A.), Provenzale, Spiegel and Tresser (I.B.M.) have studied the possibility of distinguishing between intermittency produced deterministically and stochastically. This issue arises, for example, in ascertaining what the nature of the mechanism producing solar grand minima may be. The distinction can be made by using suitably fine tricks but for these to work the data must be numerous and of good quality. They have also made similar studies on distinguishing between stochastic resonance and (what they have called) chaotic resonance.

Balmforth (Nottingham), Martens (I.B.M), Provenazale, Spiegel, Tresser and Wu (I.B.M.) have shown how multiplicative noise can turn the spectrum of a deterministic chaotic process from blue to red.

Murante (Istituto di Cosmogeofisica, Turin), Provenzale, Spiegel and Thieberger (Ben Gurion U., Israel) have studied the usefulness of a description of the spatial distribution of the galaxies as groupings around density singularities distributed randomly in space. They find that the singularity picture works as well as the more conventional fractal description from the viewpoint of scaling laws.

Prendergast and Slyz are continuing the development of a multifluid code for problems of galactic formation and evolution, based on the BGK hydrocode of Prendergast and Xu.

G. Chudnovsky (Brooklyn Polytech) and Prendergast are looking into the application of high-order symplectic integrators on a grid to dynamical problems in a few degrees of freedom. It is well known that these schemes are ''error free'' in the sense that they exactly integrate a discrete version of the problem, but there are aspects of Hamiltonian mechanics which are not properly represented. For example, all bounded orbits are periodic in these schemes, but it is not clear which of these are low-resolution versions of truly periodic orbits, and which are artifacts of the finite resolution. We hope to clarify this situation using a combination of numerical and analytic methods.

9. LABORATORY ASTROPHYSICS & INSTRUMENT DESIGN

Aprile, Egorov, Giboni, Kozu, and Silver have continued work on the development of a Balloon-Borne Liquid Xenon Gamma-Ray Imaging Telescope (LXeGRIT) for high energy astrophysics. The telescope images cosmic γ-rays through their Compton interactions in a liquid xenon time projection chamber (LXeTPC), a sensitive detector which combines three-dimensional position resolution with good spectroscopy and high detection efficiency. The LXeTPC, developed by the Columbia team with collaborators at Waseda University, the University of New Hampshire, and NASA/MSFC, was integrated as balloon payload and successfully flown twice this year on high altitude balloons from Palestine, TX. The main goal of these initial flights was to demonstrate the feasibility of the technology in a space environment and to measure for the first time the background rate in a liquid xenon detector operated at balloon altitude. The detection of cosmic γ-rays in the energy range 0.3–30 MeV by the LXeGRIT instrument represents a milestone for the application of the liquid xenon imaging technology in a next generation Compton telescope. With these and subsequent flight data the group aims to confirm their calculations of the instrument angular resolution and background rejection capability. Having completed this initial phase of engineering tests and calibration in space, the efforts will now concentrate on data analysis and on the preparation of the telescope for a 1998 turnaround flight, with observations of MeV emission from Cygnus X-1 as primary science goal.

Craig, Hailey, Kahn, Hong and Keck are working on analysis of data taken in the 1995 flight of the γ-ray arcminute telescope imaging system (GRATIS). GRATIS produced arcminute resolution images of cosmic sources in the 20–200 KeV energy band. The highest priority targets under examination are GRS 1915, Cen A and 4U 1700, which is a calibration target. Final positioning of GRS 1915, along with a timing analysis, is expected to be completed shortly. There are radio and IR observations taken within 24 hrs of the GRS 1915 observation. A detailed model of the GRATIS background has been produced by Keck and is being compared with observations. GRATIS is approved for a reflight.

Hong and Hailey are continuing their work on supershields for suppression of neutron background in space. They have produced an extremely detailed model for generating neutron source functions in spacecraft material. The model uses as input the measured and theoretical neutron source function for the atmosphere, along with a statistical model of the nucleus to correct for the difference between atmospheric source function and material of arbitrary atomic weight and number. They have also produced a computer code which determines all the decay modes of the semiconductor material CZT in order to assess the effects of neutron exposure on this material. In collaboration with F. Harrison and collaborators at Caltech they have used the neutron source function/CZT code to evaluate overall background in balloon and satellite-based CZT detectors. Hong is conducting laboratory measurements on candidate supershield geometries using neutron sources to better understand how much neutron suppression an actual in-flight shield might obtain.

Kaaret, Novick, and Tomsick continue work on the Stellar X-Ray Polarimeter (SXRP) for the Spectrum-X-Gamma mission. The flight model of the SXRP has been completed and has undergone calibration and environmental testing. When launched, the SXRP will provide an order of magnitude in-

crease in polarization sensitivity relative to any previously flown X-ray polarimeter.

Craig, Hailey, and Jimenez-Garate are working on the High Energy Focussing Telescope (HEFT) payload, a balloon-borne, multilayer-coated, grazing incidence telescope for use in the 20–100 KeV energy band. HEFT is a collaboration between Columbia, Caltech, the Danish Space Research Institute and Lawrence Livermore National Laboratory. HEFT will obtain 1 arcminute resolution images and have sensitivities in typical balloon observations which are more than an order of magnitude better than a 2 week observation with RXTE/HEXTE experiment. Epoxy-replicated aluminum foil mirrors have been fabricated which have lower surface roughness and better reflectivity than the current state-of-the art and do not require elaborate vacuum processing for production. In addition, great success has been obtained with thermally-formed glass optics. These optics have lower surface roughness, higher reflectivity and better figure than has ever been obtained with epoxy-replicated aluminum foils. Prototype shells have shown surface figures of $\sim$45 arcsec. The limitations on figure are well understood and it is anticipated that much better shells will soon be produced for use in hard X-ray optics.

Craig and Hailey are working on the X-ray Constellation Mission (HTXS), on both the hard X-ray telescope and the spectroscopy telescope. On the spectroscopy telescope they are collaborating with L. Cohen (CfA) and M. Schattenberg (MIT) on thermally-formed glass optics. Using more elaborate procedures than those being employed on HEFT, the goal is to demonstrate sub-15 arcsecond figure in glass optics.

Craig and Hailey have completed the commissioning of the Automated Multi-object Spectrograph (AMOS), a fiber-fed optical positioner developed for Lick Observatory in collaboration with Principal Investigator Jean Brodie (UC Santa Cruz). Also involved in AMOS is Lawrence Livermore National Laboratory. Hailey and Craig, in collaboration with Brodie and J. Huchra (CfA) are analyzing data taken with AMOS at the 3 meter telescope. Hailey, Craig, and Brodie are also analyzing data from a survey of the Cygnus Loop, and an analysis of velocity dispersion of *ROSAT* selected clusters of galaxies.

Craig, Hailey, Helfand, Kahn, and Kamionkowski along with Caltech, Princeton and Lawrence Livermore National Laboratory, TRW, and Omitron Corp. have written a proposal called Burst Observatory for the Localization of Transients (BOLT) which has been selected as an alternate mission in the recent NASA SMEX announcement of opportunity. They will conduct a Phase A study of the BOLT concept over the next 5 months. Hailey is the Principal Investigator.

Gu, Savin, and Kahn and their collaborators P. Beiersdorfer, G.V. Brown, and D.A. Liedahl (LLNL) have continued their experimental investigations of line emission from iron L-shell ions in optically thin, collisionally ionized plasmas. In astronomical plasmas, transitions in Fe XVII to Fe XXIV of the type $n \geqslant 3 \rightarrow n = 2$ are one of the dominant forms line emission in the 6 Å to 18 Å spectral region. Recent *Advanced Satellite for Cosmology and Astrophysics (ASCA)* spectra exhibit discrepancies with the relative line intensities of various Fe XXIII and XXIV L-shell emission lines predicted by standard plasma emission codes. New distorted wave calculations of Fe XXIII and Fe XXIV electron impact excitation rate coefficients by Liedahl, Osterheld, & Goldstein (1995, Ap.J., 438, L115) appear to provide better agreement with the *ASCA* data. Using the Lawrence Livermore electron beam ion trap (EBIT), Savin et al. (1996, Ap.J., 470, L73) measured the relative line emission of several Fe XXIV $3 \rightarrow 2$ and $4 \rightarrow 2$ lines at electron energies significantly greater than the excitation threshold energies of the lines observed and found good agreement with the calculations of Liedahl *et al.* The calculations of Liedahl *et al.*, however, do not include the effects of resonant excitation (RE). They do account for the resonant process dielectronic recombination (DR). DR is, however, incompletely accounted for by the standard plasma emission codes and RE not at all. DR and RE are important at electron energies near threshold. Using EBIT, we have measured the RE and DR contributions to Fe XXIV $3 \rightarrow 2$ line emission at energies around threshold. We find, at electron temperatures near Fe XXIV peak emissivity, that DR enhances line emissivity by $\sim$ 20% and RE by $\sim$ 10%. Our results indicate the data used by the standard plasma emission codes can underestimate line emissivities by at least $\sim$ 30%.

Kahn and his collaborators V. Decaux, P. Beiersdorfer (LLNL) and V.L. Jacobs (Naval Research Lab) have carried out laboratory measurements, using EBIT, of high resolution spectra of Fe XVIII to Fe XXV Kα emission under transient conditions similar to those that are believed to exist in stellar flares and young supernova remnants. Taking advantage of our high spectral resolution ($\lambda/\Delta\lambda \geqslant 2000$), we identify a number of transitions that can serve as diagnostics of ionizing plasmas. By varying the excitation energy in the experiments, we constrain the effects of the electron distribution on these diagnostic lines. Using our measured line ratios, we deduce values for the ionization time, $\eta = N_e t$, in the plasma, which agree with the actual values to $\sim$20% accuracy. This adds confidence to our ability to derive similar constraints on astrophysical plasmas from remote X-ray spectroscopic observations.

Kahn and his collaborators B.J. Wargelin (Harvard-Smithsonian CfA), P. Beiersdorfer, D.A. Liedahl (LLNL), and S. von Goeler (Princeton) have analyzed the spectra of highly ionized iron species between 7 and 9 Å have using data obtained at the Princeton Large Torus tokamak under plasma conditions similar to those present in stellar flares. The wavelengths of many iron lines are measured with very high accuracy ($\lambda/\Delta\lambda$ up to 40,000). Theoretical spectra that predict both the wavelength and intensity of Fe emission lines are compared with the observed spectra and used to make accurate line identifications. Virtually all the observed iron lines are found to arise from $n = 4$, 5, and $6 \rightarrow 2$ transitions in Fe XXI to Fe XXIV, and many lines are identified for the first time. Several transitions have been shown to have diagnostic applications, and a detailed analysis of the density sensitivity of Fe XXII lines has been carried out. In addition, a number of emission lines from heliumlike Mg XI and Al XII, which may be useful as plasma diagnostics, have

been observed in the 7–9 Å wavelength range. We have found that some of the more important Mg XI and Al XII lines are, in fact, blended with lines from Fe XXII, XXIII, and XXIV. These previously unknown blends will need to be taken into account when attempting to use these Mg and Al lines as plasma diagnostics.

Savin and Kahn and their collaborators J. Linkemann, M. Schmitt, D. Schwalm, A. Wolf (Max-Planck-Institute for Nuclear Physics), T. Bartsch, A Müller, S. Schippers (Justus-Liebig-Universität), and M.H. Chen and D.A. Liedahl (LLNL) experimentally demonstrated the importance of fine-structure core excitations for dielectronic recombination (DR) in photoionized gas. At the low electron temperatures existing in photoionized gases with cosmic abundances, DR proceeds primarily via $nl_j \rightarrow nl'_{j'}$ excitations of core electrons ($\Delta n=0$ DR). At these temperatures, the dominant DR channel often involves $2p_{1/2} \rightarrow 2p_{3/2}$ fine-structure core excitations, which are not included in LS-coupling calculations or the Burgess formula. Using the heavy-ion storage ring at the Max-Planck-Institut für Kernphysik in Heidelberg, Germany, we have verified experimentally for Fe XVIII that DR proceeding via this channel can be significant in relation to other recombination rates, especially at the low temperatures characteristic of photoionized gases. At temperatures in photoionized gases near where Fe XVIII peaks in fractional abundance, our measured Fe XVIII to Fe XVII $\Delta n=0$ DR rate coefficient is a factor of ~ 2 larger than predicted by existing theoretical calculations. We have carried out new fully-relativistic calculations using intermediate-coupling which include the $2p_{1/2} \rightarrow 2p_{3/2}$ channel and agree to within $\sim 30\%$ with our measurements. DR via the $2p_{1/2} \rightarrow 2p_{3/2}$ channel may also have spectroscopic implications, providing unique spectral signatures at soft X-ray wavelengths which could provide good electron temperature diagnostics.

Savin, Gu, and Kahn and their collaborators B. Beck, P. Beiersdorfer, G V. Brown, and J. Crespo López-Urrutia (LLNL) are using the Lawrence-Livermore EBIT to simulate a single electron density plasma with a Maxwell-Boltzmann electron energy distribution. Our aim is to produce the ionization balance appropriate for a Maxwellian plasma and to observe the resulting line emission. Achieving the ionization balance appropriate for a Maxwellian plasma is important because line emission from a given charge state is coupled to the one lower charge state by inner shell ionization and to the one higher charge state by dielectronic and radiative recombination. They have recently demonstrated that the concept of producing quasi-Maxwellian plasmas can be implemented in EBIT by sweeping in time both the electron beam energy and electron gun anode voltage. Because the electron beam current varies as $n_e E^{1/2}$, we must also sweep the anode (extraction) voltage of the electron gun in EBIT synchronously with the beam energy, so as to vary the current in such a way as to keep the electron density nearly constant. Initial results have demonstrated that the concept of producing quasi-Maxwellian plasmas can be implemented in EBIT by sweeping in time both the electron beam energy and the electron gun anode voltage.

A team lead by Kahn has completed fabrication and testing of the first of two flight models of a critical component of the Reflection Grating Spectrometer experiment which will fly on the European Space Agency's X-Ray Multi-Mirror Mission (XMM) in August of 1999. XMM, is one of four ''cornerstone'' missions of the European Space Agency's research program in the space sciences. The Reflection Grating Spectrometer will provide the first high sensitivity, high resolution X-ray spectra of cosmic sources. It will enable detailed, quantitative measurements of such important information as the temperature, density, and chemical content of cosmic plasmas ranging from the shock-heated interstellar media surrounding recent supernova explosions to the irradiated accreting gases orbiting massive black holes at the centers of the nuclei of active galaxies. The component developed at Columbia is a precision-aligned array of lightweighted reflection gratings which both focus and disperse the collected X-ray light. This work is supported by NASA as the primary US contribution to the XMM mission. Others involved with the project at Columbia include researchers Paerels and Rasmussen, graduate students Cottam and Spodek, mechanical engineer Todd Decker, and research associate Marcela Stern.

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