

Princeton University
Princeton University Observatory
Department of Astrophysical Sciences
Peyton Hall, Princeton, New Jersey 08544 USA

[S0002-7537(90)01601-8]

This report provides a summary and bibliography for the research activities at the Princeton University Observatory and Department of Astrophysical Sciences during the period July 1, 1998 to June 30, 1999.

1. PERSONNEL

During the reporting year the research staff consisted of Neta Bahcall, Renyue Cen, Bruce Draine, Jeremy Goodman, J. Richard Gott, James Gunn, Edward Jenkins, Gillian Knapp, Russell Kulsrud, Jeremiah Ostriker, Bohdan Paczyński, David Spergel, Michael Strauss, Scott Tremaine and Edwin Turner, as well as postdoctoral fellows David Bowen, Greg Bryan, Neil Cornish, Romeel Davé, Željko Ivezić, Alexander Lazarian, Aigen Li, Robert Nelson, Alexandre Refregier, David Schlegel, Todd Tripp, Michael Vogeley, and Yun Wang. Christopher O’Dea (STScI), Stefi A. Baum (STScI), and Leopoldo Infante (P. Univ. Católica de Chile) held visiting positions. Greg L. Bryan accepted a position at MIT. Alexander Lazarian accepted a 5-year research fellowship at CITA. Alexandre Refregier accepted a position at Cambridge University. New graduate students this year are Lei Hao, Hiranya Peiris, Bartosz Pindor, Roman Rafikov, Stuart Wyithe, and Qingjuan Yu. New postdoctoral fellows this year are David Bowen, Neil Cornish, Romeel Davé, Aigen Li, Robert Nelson, and David Schlegel. The Lyman Spitzer, Jr. Spring Lecture series was given by Alexei Filipenko of the Univ. of California, Berkeley. Scott Tremaine was promoted to chair and David N. Spergel was promoted to associate chair.

2. RESEARCH PROGRAM

2.1 Cosmological Models

N. Bahcall and X. Fan, in the paper “A Lightweight Universe?” summarized the best constraints placed on the mass density of the universe as determined from several independent observational methods. The methods include the observed mass-to-light ratio of galaxies, groups and clusters as a function of scale; the observed baryon fraction in clusters; and the evolution of cluster abundance. They showed that the independent methods all indicate a sub-critical mass-density, insufficient to halt the universal expansion. The different techniques reveal a consistent picture of a lightweight universe with $\Omega \sim 0.2 - 0.3$.

N. Bahcall, J. Ostriker, S. Perlmutter and P. Steinhardt, in an invited review paper for *Science* “The Cosmic Triangle: Revealing the State of the Universe,” introduce the Cosmic Triangle as a way of representing the past, present, and future status of the universe. Our current location within the cosmic triangle is determined by the answers to three questions: How much matter is in the Universe? Is the expansion

rate slowing down or speeding up? and, Is the universe flat? They review recent observations and suggest a best-fit universe that is lightweight, is accelerating, and is flat. The acceleration, if confirmed by upcoming experiments, implies the existence of cosmic dark energy that overcomes the gravitational self-attraction of matter and causes the expansion to speed up.

N. Bahcall, in several invited reviews, summarized the current observational determination of cosmological parameters - including the mass-density of the universe, the cosmological constant, and the amplitude of mass fluctuations - using different independent methods. A consistent picture is beginning to emerge, as discussed above.

Cen proposed to test all CDM models at moderate to high redshifts using a suite of observations. The COBE microwave background temperature fluctuations and the abundance of local rich clusters of galaxies provide the two most powerful constraints on cosmological models. When all variants of the standard cold dark matter (CDM) model are subject to the combined constraints, the power spectrum of any model is fixed to $\sim 10\%$ accuracy in both the shape and overall amplitude. These constrained models are not expected to differ dramatically in their local large-scale structure properties. However, their evolutionary histories differ with differences being dramatically larger towards higher redshift. In particular, it should be true that any statistical measure that probes a rapidly diminishing tail of some distribution should provide a sensitive test at some sufficiently high redshift, when the objects in question are rare and hence in the tail. Six standardized COBE and cluster normalized CDM models are examined with respect to a large set of independent observations. The observations include correlation function of rich clusters of galaxies, galaxy power spectrum, evolution of rich cluster abundance, gravitational lensing by moderate-to-high redshift clusters, Ly_α forest, damped Ly_α systems, high redshift galaxies, reionization of the universe and future CMB experiments. It seems that each of the independent observations examined is potentially capable of distinguishing between at least some of the models. The combined power of several or all of these observations is tremendous. Thus, they appear to be on the verge of being able to make dramatic tests of all models in the near future using a rapidly growing set of observations, mostly at moderate to high redshift. Consistency or inconsistency between different observed phenomena on different scales and/or at different epochs with respect to the models will have profound implications for the theory of growth of cosmic structure.

Martin Bucher (DAMTP) and David Spergel in “Is the Dark Matter A Solid?” proposed that a smooth unclustered dark matter component with negative pressure could reconcile a flat universe with the many observations that find a density in ordinary, clustered matter well below the critical

density and also explain the recent high redshift supernova data suggesting that the expansion of the universe is now accelerating. For a perfect fluid negative pressure leads to instabilities that are most severe on the shortest scales. However, if instead the dark matter is a solid, with an elastic resistance to pure shear deformations, an equation of state with negative pressure can avoid these short wavelength instabilities. Such a solid may arise as the result of different kinds of microphysics. Two possible candidates for a solid dark matter component are a frustrated network of non-Abelian cosmic strings or a frustrated network of domain walls. If these networks settle down to an equilibrium configuration that gets carried along and stretched by the Hubble flow, equations of state result with $w = -1/3$ and $w = -2/3$, respectively. One expects the sound speeds for the solid dark matter component to comprise an appreciable fraction of the speed of light. Therefore, the solid dark matter does not cluster, except on the very largest scales, accessible only through observing the large-angle CMB anisotropy. In this paper, they develop a generally-covariant, continuum description for the dynamics of a solid dark matter component. They derive the evolution equations for the cosmological perturbations in a flat universe with CDM+(solid) and compute the resulting large-angle CMB anisotropy. The formalism presented here applies to any generalized dark matter with negative pressure and a non-dissipative resistance to shear.

Neil Cornish and David Spergel in ‘‘A Small Universe After All?’’ (astro-ph/9906401) discuss the possibility that the universe is finite. They discuss using the cosmic microwave background radiation to measure both the geometry and topology of the universe. Previous work argued that the COBE-DMR data already rule out models that are multiply connected on scales smaller than the particle horizon. They show the opposite is true: compact (small) hyperbolic universes are favored over their infinite counterparts. For a density parameter of $\Omega_o = 0.3$, the compact models are a better fit to COBE-DMR (relative likelihood ~ 20) and the large-scale structure data (σ_8 increases by ~ 25).

Yun Wang, David Spergel, and Michael Strauss carried out a theoretical analysis of the constraints one can put on the primordial power spectrum by combining data from future redshift surveys and future maps of the cosmic microwave background. They found that the data should be sensitive to subtle steps in the primordial power spectrum, as predicted in certain models of inflation.

R. Croft (Harvard/CfA), W. Hu (IAS), and R. Davé have obtained cosmological limits on the neutrino mass by measuring the amount of power on intermediate scales at high-redshift using the flux distribution in the Ly α forest. They place a conservative upper limit of $m_\nu \lesssim 5$ eV (total mass of all neutrino species), if $0.2 \lesssim \Omega_m \lesssim 0.5$, as is currently favored.

P. Bode altered an existing cosmological N-body code to include a Quintessence component (Quintessence is a time evolving, spatially inhomogeneous energy component with negative pressure and an equation of state $w_Q < 0$). In work with C. Ma (U. Penn.), R. Caldwell (Princeton Physics Dept.) and L. Wang (Columbia) a simple analytic approxi-

mation (calibrated to the N-body models) was derived for the linear and fully evolved nonlinear mass power spectrum for a range of plausible Quintessence cosmologies.

J. P. Ostriker, L. Wang (Columbia), R. R. Caldwell and P. J. Steinhardt presented a comprehensive study of the observational constraint on spatially flat cosmological models containing a mixture of matter and quintessence — a time varying, spatially inhomogeneous component of the energy density of the universe with negative pressure. Their study also includes the limiting case of a cosmological constant. They classify the observational constraints by redshift: low redshift constraints include the Hubble parameter, baryon fraction, cluster abundance, the age of the universe, bulk velocity and the shape of the mass power spectrum; intermediate redshift constraints are due to probes of the redshift-luminosity distance based on type Ia supernovae, gravitational lensing, the Lyman-alpha forest, and the evolution of large scale structure; high redshift constraints are based on measurements of the cosmic microwave background temperature anisotropy. Mindful of systematic errors, they adopt a conservative approach in applying these observational constraints. They determine that the range of Quintessence models in which the ratio of the matter density to the critical density is $0.2 \lesssim \Omega_m \lesssim 0.5$ and the effective, density-averaged equation-of-state is $-1 \leq w \leq -0.2$, is consistent with the most reliable, current low redshift and microwave background observations at the 2σ level. Factoring in the constraint due to the recent measurements of type Ia supernovae, the range for the equation-of-state is reduced to $-1 \leq w \leq -0.4$, where this range represents models consistent with each observational constraint at the 2σ level or better (concordance analysis). A combined maximum likelihood analysis suggests a smaller range, $-1 \leq w \leq -0.6$. They find that the best-fit and best-motivated models lie near $\Omega_m = 0.33$, with an effective equation-of-state $w = -0.65$ and $h = 0.65$ and are consistent with a spectral index $n_s = 1$.

L. -X. Li has constructed some time machines from anti-de Sitter space. One is constructed by identifying points related via boost transformations in the covering space of anti-de Sitter space. The others are constructed by gluing an anti-de Sitter space to a de Sitter space, which could describe an anti-de Sitter phase bubble living in a de Sitter phase universe. Self-consistent vacua for a massless conformally coupled scalar field are found for these time machines, whose renormalized stress-energy tensors are finite and solve the semi-classical Einstein equations. The extensions to electromagnetic fields and massless neutrinos are discussed. Li has argued that, in order to make the results consistent with Euclidean quantization, a new renormalization procedure for quantum fields in Misner-type spaces (Misner space, Misner-like de Sitter space, and Misner-like anti-de Sitter space) is required. Li has proposed such a ‘‘self-consistent’’ renormalization procedure. With this new renormalization procedure, self-consistent vacua exist for massless conformally coupling scalar fields, electromagnetic fields, and massless neutrinos in these Misner-type spaces.

L. -X. Li and J. R. Gott have investigated a model of an inflationary universe in Kaluza-Klein theory, which is a four-dimensional de Sitter space plus a one-dimensional compac-

tified internal space. They have found that the energy scale for inflation can be predicted from the fine-structure constant in a self-consistent solution of the semi-classical Einstein equations including the Casimir effect. From the observed value of the fine-structure constant, Li and Gott has obtained an energy scale for inflation of $\epsilon = 1.84 \times 10^{16} g_*^{1/4}$ Gev, where g_* is a dimensionless number depending on the spin and number of matter fields existing in the universe. This value is consistent with the values often discussed for inflation and grand unification. Li and Gott have also found that the wave function for this model predicts a high probability for forming such universes, independent of the value of the cosmological constant. The tunneling probability favors the creation of inflationary universes with a compactified dimension, over those with all macroscopic dimensions.

Yun Wang has studied the effective use of type Ia supernovae (SNe Ia) as cosmological probes in a series of three papers. Type Ia supernovae (SNe Ia) can be calibrated to be good standard candles at cosmological distances.

In the first SN Ia paper, Yun Wang proposed a supernova pencil beam survey that could yield between dozens to hundreds of SNe Ia in redshift bins of 0.1 up to $z = 1.5$, which would complement space based SN searches, and enable the proper consideration of the systematic uncertainties of SNe Ia as standard candles, in particular, evolution and gravitational lensing. She simulated SNe Ia luminosities by adding weak lensing noise (using empirical fitting formulae) and intrinsic scatter in SN Ia absolute magnitudes to standard candles placed at random redshifts. She showed that flux-averaging is powerful in reducing the combined noise due to lensing and intrinsic scatter. The SN number count is not sensitive to matter distribution in the universe; it can be used to test models of cosmology and to measure the SN rate. The SN pencil beam survey can yield a wealth of data which should enable accurate determination of the cosmological parameters and the SN rate, and provide valuable information on the formation and evolution of galaxies. She showed that a SN pencil beam survey can be accomplished on a dedicated 4 meter telescope with a square degree field of view. This telescope can be used to conduct other important observational projects compatible with the SN pencil beam survey, such as QSOs, Kuiper belt objects, and in particular, weak lensing measurements of field galaxies, and the search for gamma-ray burst afterglows.

In the second SN Ia paper, Yun Wang studied the weak lensing of standard candles. Weak lensing leads to the non-Gaussian magnification distribution of standard candles at given redshift z , $p(\mu|z)$. In this paper, she gave accurate and simple empirical fitting formulae of the weak lensing numerical simulation results with the generalized Dyer-Roeder prescription. The smoothness parameter $\tilde{\alpha}$ essentially represents the amount of matter that can cause weak lensing of a given source. Since matter distribution in the universe is inhomogeneous, we can think of our universe as a mosaic of cones centered on the observer, each with a different value of $\tilde{\alpha}$. She defined the *direction dependent* smoothness parameter $\tilde{\alpha}$ via the Dyer-Roeder equation; there is a unique mapping between $\tilde{\alpha}$ and the magnification of a source. She found that the distribution of $\tilde{\alpha}$ at given z , $p(\tilde{\alpha}|z)$, is well de-

scribed by a modified Gaussian distribution. For the same matter distribution, i.e., the same $p(\tilde{\alpha}|z)$, different values of Ω_m and Ω_Λ can lead to very different magnification distributions. The formulae derived in this paper can be conveniently used to calculate the weak lensing effects for observed Type Ia supernovae at arbitrary redshifts.

In the third SN paper, Yun Wang studied the effect of flux-averaging on the analysis of Type Ia supernova data. She combined the type Ia supernova (SNe Ia) data from the High- z SN Search and the Supernova Cosmology Project, and binned the combined data by flux-averaging in redshift intervals of $\Delta z = 0.05$ and $\Delta z = 0.1$. She found that the unbinned data yield a Hubble constant of $H_0 = 65 \pm 1$ km s⁻¹ Mpc⁻¹ (statistical error only), a matter density fraction of $\Omega_m = 0.7 \pm 0.4$, and a vacuum energy density fraction of $\Omega_\Lambda = 1.2 \pm 0.5$. The binned data for $\Delta z = 0.1$ yield $H_0 = 65 \pm 1$ km s⁻¹ Mpc⁻¹ (statistical error only), $\Omega_m = 0.3 \pm 0.6$, and $\Omega_\Lambda = 0.7 \pm 0.7$. Her results are not sensitive to the redshift bin size. Flux-averaging leads to less biased estimates of the cosmological parameters. Comparison of the data of 18 SNe Ia published by both groups of observers yields a mean SN Ia peak absolute magnitude of $M_B = -19.33 \pm 0.25$. If the SNe Ia peak absolute luminosity changes with redshift due to evolution, our ability to measure the cosmological parameters from SNe Ia data will be significantly diminished. Assuming power-law evolution in the peak absolute luminosity, $(1+z)^\beta$, she found a strong degeneracy between the evolution power-law index β and the matter density fraction Ω_m . For $\Omega_m = 0.3$, she found that the unbinned data yields $H_0 = 65 \pm 1$ km s⁻¹ Mpc⁻¹ (statistical error only), $\Omega_\Lambda = 1.4 \pm 1.1$, and $\beta = 0.5 \pm 1.6$, and the binned data (with $\Delta z = 0.1$) yields $H_0 = 65 \pm 1$ km s⁻¹ Mpc⁻¹ (statistical error only), $\Omega_\Lambda = 0.6 \pm 1.4$, and $\beta = 0.0 \pm 1.0$.

2.2 Cosmic Microwave Background Radiation

Draine (1999) reviewed the processes by which interstellar matter can radiate at microwave frequencies, and showed that the observed dust-correlated microwave emission from the interstellar medium must be primarily due to a combination of magnetic dipole emission and rotational emission from rapidly rotating ultrasmall dust grains. The optimum frequency for CMB observations is near 90 GHz, where the dust emission has a local minimum.

In a pair of papers (astro-ph/9811252; astro-ph/9811253) David Goldberg and David Spergel have developed a formalism for calculating and measuring the Microwave Background Bispectrum, a probe of non-linear physics in the microwave background. Gravitational fluctuations along the line-of-sight from the surface of last scatter to the observer distort the microwave background in several related ways: The fluctuations deflect the photon path (gravitational lensing), the decay of the gravitational potential produces additional fluctuations (ISW effect) and scattering off of hot gas in clusters produce additional fluctuations (Sunyaev-Zel'dovich effect). Even if the initial fluctuations generated at the surface of last scatter were Gaussian, the combination of these effects produce non-Gaussian features in the micro-

wave sky. They discuss the microwave bispectrum as a tool for measuring and studying this signal. For MAP, they estimate that these measurements will enable us to determine the fraction of ionized gas and to probe the time evolution of the gravitational potential. They also compute the bispectrum resulting from the 2nd order Rees-Sciama effect, and find that is undetectable with current and upcoming missions.

David Spergel was part of a study outlining science goals for cosmic microwave background observations in the post-Planck era (astro-ph/9907276). Over the coming decade, the Microwave Anisotropy Probe and Planck missions will provide low noise maps of the temperature of the cosmic microwave background (CMB). These maps will allow measurement of the power spectrum of the CMB with measurement noise below cosmic variance for $l < 1500$. It is anticipated that no further all sky CMB temperature observations will be needed after Planck. There are, however, other CMB measurements for which Planck will be not the end but the beginning. Following Planck, precise CMB polarization observations will offer the potential to study physical processes at energies as high as 10^{19} GeV. In addition, arcminute scale, multi-frequency observations will allow study of the early phases of the formation of large-scale structure in the universe.

In collaboration with David Spergel, N. Cornish studied how the shape of the universe affects the cosmic microwave background radiation. They produced simulations of the microwave sky in a number of compact versions of the usual hyperbolic (open) Friedman-Robertson-Walker model, and found these models to be a good fit to the COBE-DMR data. They also verified that these models could be experimentally distinguished from their infinite counterparts by applying the ‘‘match circles test’’ to search for correlations in the microwave radiation. They have submitted these findings to Physical Review Letters. Before they could arrive at these results they first had to solve a problem in applied mathematics, namely, how to find the wave spectrum in compact hyperbolic spaces. A description of their approach to solving this problem has been submitted to Experimental Mathematics.

Oleg Gnedin and Nickolay Gnedin (Berkeley) solved the Boltzmann equation for cosmological neutrinos around the epoch of the electron-positron annihilation in order to verify the freeze-out approximation and to compute accurately the cosmological neutrino distribution function. They find the radiation energy density to be about 0.3% higher than predicted by the freeze-out approximation. As a result, the spectrum of the cosmic microwave background anisotropies changes by $\sim 0.3\%–0.5\%$, depending on the angular scale, and the amplitude of the mass fluctuations on scales below about $100 h^{-1}$ Mpc decreases by about $0.2\%–0.3\%$ (CMB).

2.3 Large-Scale Structure

N. Bahcall, in collaboration with X. Fan (graduate student), investigated the observed evolution of the abundance of clusters of galaxies and used it to place strong constraints on cosmological parameters: the mass-density of the universe, Ω , and the amplitude of mass fluctuations on $8h^{-1}$ Mpc scale, σ_8 . They used the most massive distant clusters of galaxies observed so far, at $z > 0.5$, to constrain these pa-

rameters. They showed that the existence of these massive clusters (with masses comparable to twice the mass of Coma) at these early epochs strongly rules out Gaussian models with critical mass density ($\Omega = 1$, $\sigma_8 \approx 0.5$); such models form massive clusters only recently and predict essentially *no* high-mass clusters at these redshifts ($\sim 10^{-5}$ clusters expected at $z > 0.65$ and $\sim 10^{-3}$ clusters at $z > 0.5$ as compared with the 1 ($z > 0.65$) and 3 ($z > 0.5$) clusters observed). From these observations, they derive best-fit values of $\Omega = 0.2 (+0.3, -0.1)$ and $\sigma_8 = 1.2 (\pm 0.4)$ (95%). The high $\sigma_8 \sim 1$ amplitude, comparable to that observed for galaxies, suggests that mass approximately traces light on large scales.

Cen, in collaboration with J. Einasto (Estonia) et. al., has calculated the mean power spectrum of all galaxies using published power spectra of galaxies and clusters of galaxies. On small scales they use the power spectrum derived from the 2-dimensional distribution of APM galaxies, since this sample is not influenced by redshift distortions and is the largest and deepest sample of galaxies available. On large scales they use power spectra derived from 3-dimensional data for various galaxy and cluster samples which are reduced to real space and in amplitude to the power spectrum of APM galaxies. They find that available data indicate the presence of two different populations in the nearby Universe. Clusters of galaxies sample a relatively large region in the Universe where rich, medium and poor superclusters are well represented. Their mean power spectrum has a spike at wavenumber $k = 0.05 \pm 0.01 h \text{ Mpc}^{-1}$, followed by an approximate power-law spectrum of index $n \approx -1.9$ towards small scales. Some galaxy surveys (APM 3-D, IRAS QDOT, and SSRS+CfA2 130 Mpc) have similar spectra. The power spectrum found from LCRS and IRAS 1.2 Jy surveys is flatter around the maximum, which may represent regions of the Universe with medium-rich and poor superclusters. Differences in power spectra for these populations may partly be due to the survey geometries of the datasets in question and/or to features of the original data analysis.

Cen, in collaboration with J. Einasto (Estonia) et. al., suggests a new method to determine the bias parameter of galaxies relative to matter. The method is based on the assumption that gravity is the dominating force which determines the formation of the structure in the Universe. Due to gravitational instability matter flows out of under-dense regions toward high-density ones. To form a galaxy the density of matter within a certain radius must exceed a critical threshold (Press-Schechter limit), thus the galaxy formation is a threshold process. In low-density environments (voids) galaxies do not form and matter remains in primordial form. They estimate the value of the threshold density which divides the matter into two populations, a low-density population in voids and a clustered population in high-density regions. They investigate the influence of the presence of these two populations to the power spectrum of matter and galaxies. They find that the power spectrum of clustered particles (galaxies) is similar to the power spectrum of matter. They show that the fraction of total matter in the clustered population determines the difference between amplitudes of fluctuations of matter and galaxies, i.e. the bias factor.

To determine the fraction of matter in voids and clustered population they perform numerical simulations. The fraction of matter in galaxies in the present epoch is found using a calibration through the σ_8 parameter. They find $\sigma_8 = 0.89 \pm 0.09$ for galaxies, $\sigma_8 = 0.68 \pm 0.09$ for matter, and the biasing factor of the clustered matter (galaxies) relative to all matter $b_{gal} = 1.3 \pm 0.13$.

Cen, in collaboration with J. Einasto (Estonia) et. al., compared the observed power spectrum of matter found in Papers I and II (see above) with analytical power spectra. They extrapolate the observed power spectra on small scales to find the linear power spectrum of matter. They consider spatially flat cold and mixed dark matter models with cosmological constant as well as open models. They fix the Hubble constant and the baryon density in the middle of the allowed range and vary the density parameter and the cosmological constant. They determine the primordial power spectrum of matter using the power spectrum of matter and the transfer functions of analytical models. They take two different spectra suggested by observations: with a sharp maximum at $120h^{-1}\text{Mpc}$ and with a broader one, as found for regions with rich and medium rich superclusters of galaxies, respectively. For both models, the primordial power spectra have a break in amplitude; in the case of the spectrum with a sharp maximum the break is sharp. They conclude that a scale-free primordial power spectrum is excluded if presently available data on the distribution of clusters and galaxies represent the true mass distribution of the Universe.

Turner, Y. Suto (U. Tokyo), T. Yamada and I. Tanaka (Tohoku U.) are analyzing the faint galaxy population present in a series of very deep SPICAM drift scans obtained with the APO 3.5-meter in a field contained an alleged supercluster of quasars with redshifts of 1.01. If confirmed by the presence of a ‘‘Great Wall’’ type supercluster in the galaxy distribution, this structure would challenge many theories of structure formation due to its large size and amplitude at high redshift. The optical data is being combined with x-ray and IR images to further probe the overall mass distribution in this region.

Working with J. Ostriker, P. Bode has developed an efficient new code to study the formation of large-scale structure. Called Tree-Particle-Mesh (TPM), this code combines the Particle-Mesh method for long-range forces with short-range forces determined by the Tree approach. Preparations are underway to carry out simulations with this code combining large volumes ($1000\text{ Mpc}/h$) with high mass and force resolution (using a billion particles and a maximum spatial dynamic range of 70,000). Such a large volume will reduce cosmic variance and give a statistically meaningful sample of clusters of galaxies (especially at high redshift) to facilitate comparisons with observations from next generation of X-ray cluster surveys such as Chandra, XMM and Astro-E. At the same time, the high resolution will make it possible to map out the gravitational lensing potentials of clusters of galaxies and large-scale structure, which can be compared with the next generation of galaxy and quasar surveys such as the SDSS.

Michael Strauss wrote two major reviews about redshift

surveys and cosmology, which were published in *Nature*, and in a textbook, *Formation of Structure in the Universe*, eds. A. Dekel and J.P. Ostriker.

Strauss and Jeff Willick (Stanford) completed an analysis comparing existing Tully-Fisher peculiar velocity data with the velocity field predicted by the large-scale distribution of *IRAS* galaxies. They confirmed their earlier results that the model fits the observed flows well, and that $\beta \equiv \Omega^{0.6}/b$ is 0.50, with very small error bars.

Strauss worked with Marc Davis and Jonathan Baker (Berkeley), Ofer Lahav (Cambridge), and Basilio Santiago (Porto Alegre) to demonstrate that the velocity fields predicted by the distribution of *IRAS* and optically-selected galaxies are in excellent agreement with one another. This result allowed them to put constraints on the relative bias of infrared- and optically-selected galaxies.

Blanton is carrying out an analysis of the relative bias between early and late-type galaxies in the Las Campanas Redshift Survey. He is finding evidence for the first time that the bias is not deterministic; that is, that early-type galaxy density is not a unique predictor of late-type galaxy density.

M. Vogeley and C. Park (Seoul) analyzed the three-dimensional power spectrum and correlation function of clusters of galaxies selected from both optical (APM, Abell) and X-ray surveys (ROSAT).

M. Vogeley and A. Connolly (Pittsburgh) investigated the impact of Galactic extinction and errors in photometry on the accuracy of statistical measures of the large-scale distribution of galaxies. Galactic extinction or photometric zero-point fluctuations cause erroneous fluctuations in the redshift-space distribution of galaxies, hence extra apparent clustering power on scales of order the angular size of these variations at the effective depth of the survey. These analyses provide guidelines for the accuracy with which the SDSS and other similar surveys must correct for extinction and for the large-scale photometric calibration.

Infante, Strauss, Bahcall and Knapp have identified close pairs and triplets of galaxies in the Sloan Digital Sky Survey commissioning imaging data. The data sets are from two of the SDSS equatorial fields covering $\sim 200\text{ deg}^2$. They have estimated the angular correlation function of these objects and appear to be appreciably more strongly clustered than are single galaxies.

Infante has used the 3.5m APO telescope to obtain *K*-band imaging of galaxies selected from the CNOC2 survey. The purpose is to distinguish the evolution of large-scale structure from the evolution of component galaxy populations over the redshift range $0.12 \leq z \leq 0.55$ from a *K*-selected sample.

Yun Wang reported her work with David Spergel and Michael Strauss on the model-independent measurement of the primordial power spectrum at the 193rd Meeting of the American Astronomical Society in Austin, Texas, and at COSMO-98 (International Workshop on Particle Physics and the Early Universe) in Monterey, California. She also reported her work with Neta Bahcall and Edwin Turner on a model-independent photometric redshift estimator, at the Workshop on Photometric Redshifts and High Redshift Galaxies, hosted by Carnegie Observatories.

2.4 Intergalactic Medium and Galaxy Formation

Cen, in collaboration with J.P. Ostriker, has used new, high resolution, large-scale, cosmological hydrodynamic galaxy formation simulations of a standard cold dark matter model (with a cosmological constant) are utilized to predict the distribution of baryons at the present and at moderate redshift. It is found that the average temperature of baryons is an increasing function of time, with most of the baryons at the present time having a temperature in the range 10^{5-7} K. Thus, not only is the universe dominated by dark matter, but more than one half of the normal matter is yet to be detected. Detection of this warm/hot gas poses an observational challenge, requiring sensitive EUV and X-ray satellites. Signatures include a soft, cosmic X-ray background, apparent warm components in hot clusters due to both intrinsic warm intra-cluster gas and warm inter-cluster gas projected onto clusters along the line of sight, absorption lines in X-ray and UV quasar spectra [e.g., O VI (1032,1038)Å lines, OVII 574 eV line], strong emission lines (e.g., O VIII 653 eV line) and low redshift, broad, low column density Ly_{α} absorption lines. They estimate that approximately 1/4 of the extragalactic soft X-ray background (SXR) (at 0.7keV) arises from the warm/hot gas, half of it coming from $z < 0.65$ and three-quarters from $z < 1.00$, so the source regions should be identifiable on deep optical images.

Cen, in collaboration with M. Blanton, J.P. Ostriker and M.A. Strauss, using a large-scale hydrodynamic simulation with heuristic criteria for galaxy formation, investigated how the galaxy field is related to physical parameters, such as the mass density and the gas temperature. In their flat Cold Dark Matter model with $\Omega_0 = 0.37$, they find that the relation between the galaxy and mass density fields is a function of scale. The bias $b(R) \equiv \sigma_g(R)/\sigma(R)$, where $\sigma_g(R)$ is the variance of galaxy counts in spheres of radius R and $\sigma(R)$ is the same for mass, varies from 2.6 at $1 h^{-1}$ Mpc to 1.2 at $30 h^{-1}$ Mpc. Including the dependence of the galaxy density on local gas temperature as well as on local mass density can fully account for this scale dependence. Galaxy density depends on temperature because gas which is too hot cannot cool to form galaxies; this causes scale dependence of $b(R)$ because local gas temperature is related to the gravitational potential, and thus contains information about the large scale density field. They show that temperature dependence generally causes $b(R)$ to vary on quasilinear and nonlinear scales, indicating that scale dependence of bias may be a generic effect in realistic galaxy formation scenarios. They find that the relationship between the galaxy and mass density fields is also a function of galaxy age. On large scales, the older galaxies are highly biased ($b \approx 1.7$) and highly correlated ($r \equiv \langle \delta\delta_g \rangle / \sigma\sigma_g \approx 1.0$) with the mass density field; younger galaxies are not biased ($b \approx 0.8$) and are poorly correlated ($r \approx 0.5$) with the mass. They argue that linear bias is inadequate to describe the relationship between galaxies and mass. They present a more physically based prescription which better fits their results and reproduces the scale dependence of the bias: $\rho_g / \langle \rho_g \rangle = L(\rho / \langle \rho \rangle)^M (1 + T/40,000K)^N$, where $L = 1.23$, $M = 1.9$, and $N = -0.66$.

Cen, in collaboration with J.P. Ostriker, analyzed a new

large-scale ($100h^{-1}$ Mpc) numerical hydrodynamic simulation of the popular Λ CDM cosmological model, including in their treatment dark matter, gas and star-formation, on the basis of standard physical processes. The method, applied with a numerical resolution of $< 200h^{-1}$ kpc (which is small compared to nearest neighbor separation of galaxies except in clusters), attempts to estimate where and when galaxies form. They then compare the smoothed galaxy distribution with the smoothed mass distribution to determine the ‘‘bias’’ defined as $b \equiv (\delta M/M)_{gal} / (\delta M/M)_{total}$ on scales large compared with the code numerical resolution (on the basis of resolution tests given in the appendix of this paper). They find that (holding all variables constant except the quoted one) bias increases with decreasing scale, with increasing galactic age or metallicity and with increasing redshift of observations. At the $8h^{-1}$ Mpc fiducial comoving scale bias (for bright systems) is 1.35 at $z = 0$ reaching to 3.6 at $z = 3$, both numbers being consistent with extant observations. They also find that $(10 - 20)h^{-1}$ Mpc voids in the distribution of luminous objects are as observed (i.e., observed voids are not an argument against CDM-like models) and finally that the younger systems should show a colder Hubble flow than do the early type galaxies (a testable proposition). Surprisingly, little evolution is found in the amplitude of the smoothed galaxy-galaxy correlation function (as a function of *comoving* separation). Testing this prediction vs observations will allow a comparison between this work and that of Kauffmann, *et al.* which is based on a different physical modeling method.

Cen, in collaboration with M. Blanton, J.P. Ostriker, M.A. Strauss and M. Tegmark, has investigated the time evolution of galaxy formation and bias in cosmological simulations. The clustering of galaxies relative to the mass distribution declines with time because: first, nonlinear peaks become less rare events; second, the densest regions stop forming new galaxies because gas there becomes too hot to cool and collapse; third, after galaxies form, they are gravitationally ‘‘debiased’’ because their velocity field is the same as the dark matter. To show these effects, they perform a hydrodynamic cosmological simulation and examine the density field of recently formed galaxies as a function of redshift. They find the bias b_* of recently formed galaxies (the ratio of the rms fluctuations of these galaxies and mass), evolves from 4.5 at $z = 3$ to around 1 at $z = 0$, on $8h^{-1}$ Mpc comoving scales. The correlation coefficient r_* between recently formed galaxies and mass evolves from 0.9 at $z = 3$ to 0.25 at $z=0$. As gas in the universe heats up and prevents star formation, star-forming galaxies become poorer tracers of the mass density field. After galaxies form, the linear continuity equation is a good approximation to the gravitational debiasing, even on nonlinear scales. The most interesting observational consequence of the simulations is that the linear regression of the star-formation density field on the galaxy density field evolves from about 0.9 at $z = 1$ to 0.35 at $z=0$. These effects also provide a possible explanation for the Butcher-Oemler effect, the excess of blue galaxies in clusters at redshift $z \sim 0.5$. Finally, they examine cluster mass-to-light ratio estimates of Ω , finding that while $\Omega(z)$ increases with z , one’s estimate $\Omega_{est}(z)$ decreases.

Cen, in collaboration with K. Nagamine and J.P. Ostriker, has computed the rest-frame comoving luminosity density in various bands as a function of redshift and the cosmic star formation rate (SFR) using a Lambda-CDM hydrodynamical galaxy simulation. They used an updated isochrone synthesis code to calculate the luminosity density. The calculated UV-luminosity density and the cosmic SFR have a steep rise from $z=0$ to 1, a moderate plateau at $z = 1 - 3$, and a slight decrease beyond $z=3$. They find that the calculated SFR agrees well with the extinction corrected data points of the optical (to submm) surveys of galaxies. They discuss the conversion between UV-luminosity density and SFR as well as the implication of their results on the effects of dust extinction. Finally, they consider the physical origin of the ‘‘Madau Plot’’ in terms of cooling time of the gas by analyzing the temperature-mass relation and the ratio of cooling time to the Hubble-time in the simulation at various redshifts.

Leo Blitz, David Spergel, Peter Teuben and Dap Hartmann continue their investigations of the possibility that the High Velocity Clouds are extra-galactic. Hierarchical structure formation models predict the existence of large numbers of low velocity dispersion dark halos. Galaxy surveys find far fewer galaxies than predicted by analytical estimates and numerical simulations. In this paper, we suggest that these dark halos are not missing, but have been merely misplaced in the galactic astronomy section of the journals: they are the High Velocity Clouds (HVCs). They review the predictions of the model for the Local Group origin of the HVCs and its implications for the formation and the evolution of our Galaxy. They describe recent observations that confirm many of earlier predictions and discuss future tests of the model.

Graduate student Michael Blanton, working with M.A. Strauss, J.P. Ostriker and R. Cen, has explored the nature of galaxy bias in large cosmological simulations. They have shown that galaxy formation is a strong function of local gas temperature, which has a modulating effect on the large-scale distribution of galaxies, giving rise to a scale-dependent bias. In addition, they have explored the evolution of bias with time, identifying the various physical processes that give rise to the evolution.

R. Davé, L. Hernquist (Harvard/CfA), N. Katz (Massachusetts), and D. Weinberg (Ohio State) have studied the intergalactic medium at low redshift by comparing cosmological hydrodynamic simulations with HST Quasar Absorption Line Key Project results. Currently favored cosmologies reproduce many observed evolutionary trends of the Ly α forest from $z = 4 \rightarrow 0$, and they find that the driving factor in the evolution of the number density of Ly α absorbers is the metagalactic photoionizing background. Ly α absorbers represent the same underlying objects at high and low redshifts, but due to Hubble expansion and evolving photoionization conditions, their observational ‘‘window’’ on these absorbers evolves with redshift, so that an absorber of given strength traces a higher overdensity at lower redshift. Also, low- z absorbers appear to trace the large-scale structure in which galaxies reside, but are seldom associated with galactic gas, in agreement with observations by Tripp, Lu and Savage, among others.

R. Davé, with L. Hernquist (Harvard/CfA), N. Katz (Massachusetts), and D. Weinberg (Ohio State), has determined the metallicity of the high-redshift intergalactic medium from CIV absorption in a Keck HIRES quasar spectrum of Q1422+231 to be $[C/H] \approx -2.5$, given an ionizing background as produced by quasars. Furthermore, OVI absorption shows that lower density gas has a lower metallicity, as might be expected in recent metal ejection scenarios. Comparing OVI and CIV absorption shows that Helium reionization has begun by $z \sim 3.5$, although a patchy ionization structure could still exist down to $z \sim 3$.

Together with R. Croft (Harvard/CfA), this group has investigated the possibility of discriminating cosmological models by comparing high-redshift quasar spectra from Keck (provided by D. Tytler and S. Burles) with hydro simulations of currently popular cosmologies. Preliminary results favor cosmologies with higher power at $z \sim 3$, such as low- Ω models.

R. Davé, with L. Hernquist (Harvard/CfA), S. Kirhakos and J. Bahcall (IAS), has preliminarily determined the metallicity of the low-redshift diffuse intergalactic medium from HST QAL Key Project data to be $-1.5 \gtrsim [C/H] \gtrsim -2$, somewhat higher than the Ly α forest metallicity at high redshift. There is also weak evidence for a gradient in metallicity with density from OVI absorption.

R. Davé has compared the formation of high-redshift galaxies in high-resolution cosmological hydro simulations with observed ‘‘Lyman-break galaxies’’ (LBGs; Steidel, *et al.*). Applying Bruzual & Charlot population synthesis models to simulated galaxies along with the Lyman-break color selection, these simulations suggest that LBGs represent the most massive galaxies at this epoch ($z \sim 3$), containing the oldest stellar populations, in agreement with independent arguments based on their clustering and biasing properties (Adelberger, *et al.*). Together with R. Somerville (Hebrew Univ.), the relationship between damped Ly α absorbers and LBGs is also being investigated.

R. Davé, L. Hernquist (Harvard/CfA), D. Weinberg (Ohio State) and N. Katz (Massachusetts) have investigated the evolution of clustering and biasing of galaxies from $z = 4 \rightarrow 0$, using a $50h^{-1}\text{Mpc}$ ΛCDM hydro simulation with $10h^{-1}\text{kpc}$ resolution. The comoving galaxy correlation function evolves only mildly, with the correlation length first decreasing then increasing with time. Galaxies begin as highly biased tracers of the mass, and become less so with time. The scale dependence of bias also decreases with time.

S.P. Oh (graduate student) investigated the future detection of the first luminous objects in free-free and H α emission. The integrated free-free emission from ionized halos creates a spectral distortion of the Cosmic Microwave Background, detectable by the planned DIMES satellite. Ionized halos may also be imaged directly in free-free emission by the Square Kilometer Array. Balmer line emission from ionized halos is detectable by the Next Generation Space Telescope. Unlike Ly α , the H α line does not suffer from resonant scattering by neutral hydrogen, and is still observable when the IGM is not fully reionized. Expected number counts and signal strengths are calculated in the context of a semi-analytic galaxy formation model.

Tripp completed a study with L. Lu (Caltech) and B. Savage (Wisconsin) of the relationship between low redshift Lyman α clouds and galaxies based on low resolution, but very high signal-to-noise, HST spectroscopy of two QSOs, H1821+643 and PG1116+215 (Tripp, *et al.* 1998). These observations show that many low z Ly α clouds are due to gas in large-scale structures rather than the gaseous halos of individual galaxies. Subsequently, Tripp, Jenkins, and Savage applied for and received HST time to observe these QSOs with the Space Telescope Imaging Spectrograph (STIS) in the far UV at high resolution ($R = 46000$). The first of these observations was executed successfully and the analysis of the physical conditions and metallicity of the low z Ly α absorbers is underway.

These new STIS observations will also be used to search for the large reservoir of intergalactic baryons in gas at $T = 10^5 - 10^7$ K predicted by hydrodynamic simulations of cosmological structure growth by Cen and Ostriker. This will be done by searching for O VI absorption lines which arise in the hot gas, which is quite difficult to observe in x-rays due to complicated foreground absorption and emission corrections. To interpret the STIS data, Cen, Tripp, Jenkins, and Ostriker are producing synthetic spectra from the cosmological simulations for comparison to the observations.

In collaboration with a team at NASA-Goddard headed by S. Heap, Tripp and Jenkins participated in the analysis of STIS observations of the high redshift QSO Q0302-003 to study He II absorption in the intergalactic medium. From the high signal-to-noise STIS spectrum several results were derived. First, the He II ‘‘proximity effect’’ is clearly detected, and analysis of the proximity profile showed that near the QSO all He II absorption is due to discrete clouds with no contribution from smoothly distributed diffuse intergalactic gas. Second, the He II Ly α opacity was measured at several redshifts, and a substantial decrease in this opacity was clearly detected at $z \approx 3$. This change in opacity could indicate an abrupt change in the ionization state of the IGM, perhaps due to completion of He reionization. Third, a well-detected gap in the He II absorption is found which matches a gap in the H I Ly α forest in redshift space. This gap is probably due to photoionization of the IGM from a local source such as an AGN. However, a different prominent gap in the H I Ly α forest still shows strong absorption by He II.

In collaboration with the STIS Instrument Definition Team, Tripp and Jenkins have observed several other QSOs (e.g., HS 1700+6416, PKS 0405-123, 3C 351) with STIS to study the nature of the QSO absorbers including their physical conditions and metallicity as well as their relationship with galaxies and larger scale structures. Analyses of the spectra are underway.

2.5 Clusters and Groups of Galaxies

N. Bahcall summarized the current observational constraints from studies of the large-scale structure of the universe, clusters and superclusters of galaxies, and their cosmological implications. The use of upcoming large-scale surveys in the optical and in X-Rays, including the Sloan Digital Sky Survey, were discussed and their impact expected in these fields highlighted.

N. Bahcall, in collaboration with J. Kepner and X. Fan (graduate students), J. Gunn and R. Lupton developed an automated method for detecting clusters of galaxies in imaging and redshift galaxy surveys. The Adaptive Matched Filter (AMF) method utilizes galaxy positions, magnitudes, and - when available - photometric or spectroscopic redshifts to find clusters and determine their redshift and richness. The AMF can be applied to most types of galaxy surveys: from two-dimensional (2D) imaging surveys, to multi-band imaging surveys with photometric redshifts of any accuracy ($2\frac{1}{2}$ D), to three-dimensional (3D) redshift surveys. The AMF can also be utilized in the selection of clusters in cosmological N-body simulations. The AMF identifies clusters by finding the peaks in a cluster likelihood map generated by convolving a galaxy survey with a filter based on a model of the cluster and field galaxy distributions. In tests on simulated 2D and $2\frac{1}{2}$ D data with a magnitude limit of $r' \approx 23.5$, clusters are detected with an accuracy of Δz 0.02 in redshift and $\sim 10\%$ in richness to $z < 0.5$. Detecting clusters at higher redshifts is possible with deeper surveys.

Y. Wang, N. Bahcall and E. Turner derived a simple empirical color-redshift relation for $z < 4$ galaxies in the Hubble Deep Field (HDF) using a linear function of three photometric colors (U - B, B - V, V - I). The dispersion between the estimated redshifts and the spectroscopically observed ones is small for relations derived in several separate color regimes; the dispersions range from $\sigma_z \approx 0.03$ to 0.1 for $z < 2$ galaxies, and from $\sigma_z \approx 0.14$ to 0.25 for $z > 2$ galaxies. They applied the color-redshift relations to the HDF photometric catalog and obtained estimated redshifts that were consistent with those derived from spectral template fitting methods. The advantage of these color-redshift relations is that they are simple and easy to use and do not depend on the assumption of any particular spectral templates; they provide model independent redshift estimates for $z < 4$ galaxies using only multiband photometry, and they apply to about 90% of all galaxies. The method was used to obtain a color-based estimate redshift catalog of HDF galaxies to $z < 4$. The estimated redshifts were used to investigate the redshift distribution of galaxies in the HDF, finding peaks in the redshift distribution that suggest large-scale clustering of galaxies to at least $z \sim 1$. The peaks are consistent with those identified in spectroscopic probes of the HDF.

Cen developed and tested a method to compute mass and auto-correlation functions of rich clusters of galaxies from linear density fluctuations, based on the formalism of Gaussian peaks (Bardeen, *et al.* 1986). The essential, new ingredient in the current approach is a simultaneous and unique fixture of the *size* of the smoothing window for the density field, r_f , and the *critical height* for collapse of a density peak, δ_c , for a given cluster mass (enclosed within the sphere of a given radius rather than the virial radius, which is hard to measure observationally). Of these two parameters, r_f depends on both the mass of the cluster in question and Ω , whereas δ_c is a function of only Ω and Λ . These two parameters have formerly been treated as adjustable and approximate parameters. Thus, for the first time, the Gaussian Peak Method (GPM) becomes unambiguous, and more importantly, accurate, as is shown here. This method is then

used to constrain all variants of the Gaussian cold dark matter (CDM) cosmological model using the observed abundance of local rich clusters of galaxies and the microwave background temperature fluctuations observed by COBE. The combined constraint fixes the power spectrum of any model to $\sim 10\%$ accuracy in both the shape and overall amplitude. To set the context for analyzing CDM models, they choose six representative models of current interest, including an $\Omega_0 = 1$ tilted cold dark matter model, a mixed hot and cold dark matter model with 20% mass in neutrinos, two lower density open models with $\Omega_0 = 0.25$ and $\Omega_0 = 0.40$, and two lower density flat models with $(\Omega_0 = 0.25, \Lambda_0 = 0.75)$ and $(\Omega_0 = 0.40, \Lambda_0 = 0.60)$. This suite of CDM models should bracket any CDM model that is currently viable. The parameters of all these models are also consistent with a set of other constraints, including the Hubble constant, the age of the universe and the light-element nucleosynthesis with Ω_b chosen to maximize the viability of each model with respect to the observed gas fraction in X-ray clusters.

Cen, in collaboration with J.P. Ostriker, has performed a variety of tests to determine the numerical resolution of the cosmological TVD eulerian code developed by Ryu, et al. (1993). Tests include 512^3 and 256^3 simulations of a $P_k \propto k^{-1}$ spectrum to check for self-similarity and comparison of results with those from higher resolution SPH and grid-based calculations (Frenk, *et al.* 1998). They conclude that in regions where density gradients are not produced by shocks the code degrades resolution with a Gaussian smoothing (radius) length of 1.7 cells. At shock caused gradients (for which the code was designed) the smoothing length is 1.1 cells. Finally, for β model fit clusters, they can approximately correct numerical resolution by the transformation $R_{core}^2 \rightarrow R_{core}^2 - (C\Delta l)^2$, where Δl is the cell size and $C = 1.1 - 1.7$. When they use these corrections on their previously published computations for the SCDM and Λ CDM models they find luminosity weighted, zero redshift, X-ray cluster core radii of $(210 \pm 86, 280 \pm 67)h^{-1}\text{kpc}$, respectively, which are consistent with observed (Jones & Forman 1992) values of $50 - 200h^{-1}\text{kpc}$. Using the corrected core radii, the COBE normalized SCDM model predicts the number of bright $L_x > 10^{43}\text{erg/s}$ clusters too high by a factor of ~ 20 and the Λ CDM model is consistent with observations.

Cen, in collaboration with C.S. Frenk (Durham) et. al., has simulated the formation of an X-ray cluster in a cold dark matter universe using 12 different codes. The codes span the range of numerical techniques and implementations currently in use, including SPH and grid methods with fixed, deformable or multilevel meshes. The goal of this comparison is to assess the reliability of cosmological gas dynamical simulations of clusters in the simplest astrophysically relevant case, that in which the gas is assumed to be non-radiative. They compare images of the cluster at different epochs, global properties such as mass, temperature and X-ray luminosity, and radial profiles of various dynamical and thermodynamical quantities. On the whole, the agreement among the various simulations is gratifying although a number of discrepancies exist. Agreement is best for proper-

ties of the dark matter and worst for the total X-ray luminosity. Even in this case, simulations that adequately resolve the core radius of the gas distribution predict total X-ray luminosities that agree to within a factor of two. Other quantities are reproduced to much higher accuracy. For example, the temperature and gas mass fraction within the virial radius agree to about 10%, and the ratio of specific kinetic to thermal energies of the gas agree to about 5%. Various factors contribute to the spread in calculated cluster properties, including differences in the internal timing of the simulations. Based on the overall consistency of results, they discuss a number of general properties of the cluster they have modelled.

Strauss and graduate student Rita Kim have explored star-galaxy separation algorithms with early commissioning data from the Sloan Digital Sky Survey. In collaboration with Neta Bahcall and former graduate student Jeremy Kepner, they have applied various cluster-finding algorithms to the data, including Voronoi tessellations and an adaptive matched filter technique. Many previously unidentified clusters have been found, including some with X-ray emission in the ROSAT data. They have shown that the cluster contrast is appreciably stronger in red than blue galaxies.

In his thesis, Oleg Gnedin studied tidal effects in clusters. High-redshift clusters of galaxies show an overabundance of spirals by a factor of 2-3, and a corresponding underabundance of S0 galaxies, relative to the nearby clusters. This morphological evolution can be explained by tidal interactions with neighboring galaxies and with the time-variable cluster potential. The efficiency of the tidal interactions depends on the size and structure of the cluster, as well as on the epoch of its formation. Therefore, evolution of galaxies needs to be studied in the context of the hierarchical cluster formation.

Gnedin followed numerically the formation and evolution of the Virgo-type clusters in each of the three cosmologies: a critical density model $\Omega_0 = 1$, an open model $\Omega_0 = 0.4$, and a flat model $\Omega_0 = 0.4$ with a cosmological constant. All three clusters are chosen to have similar masses and velocity dispersions. The tidal field along the trajectories of the identified galaxies is carefully extracted, correcting for the effects of self-interaction. The maxima of the tidal force do not always correlate with the closest approach to the cluster center. They are produced to a large extent by the local density structures, such as massive galaxies and the unvirialized remnants of groups of galaxies. Close encounters between the galaxies are significantly intensified by the substructure, with about 10 encounters per galaxy within 10 kpc in the Hubble time. These very close encounters contribute an important amount (10–50%) of tidal heating of galaxies. Overall, tidal heating is stronger in the low Ω_0 clusters.

Oleg Gnedin showed that tidal forces acting on galaxies in clusters lead to strong dynamical and morphological evolution. In order to quantify the amount of evolution, self-consistent simulations of disk galaxies are performed for a variety of galactic models in three cosmological scenarios. The realistic tidal field is extracted from the cosmological simulations of clusters in the $\Omega_0 = 1$; $\Omega_0 = 0.4$; and $\Omega_0 = 0.4, \Omega_\Lambda = 0.6$ scenarios. The galaxy models include an

exponential stellar disk and an isothermal dark matter halo. For large spiral galaxies with the rotation speed of 250 km s^{-1} , tidal interactions (1) truncate the massive halo at a radius of $30 \pm 6 \text{ kpc}$, (2) have little effect on the radial scale length, (3) thicken the disk by a factor 2 ± 0.4 , increasing Toomre's parameter to $Q > 2$ and stabilizing the disk against gravitational instabilities. Dwarf galaxies with the circular velocity of 20 km s^{-1} are completely disrupted by the external tidal field. Extended low surface brightness galaxies lose most of their stars and contribute to the diffuse intracluster light. Thus, the likely consequence of tidal shocks is to turn a large fraction of normal spirals into S0 galaxies and to deplete the LSB population. With regard to cosmological scenario, at a given cluster velocity dispersion the low Ω_0 models produce stronger tidal forces. Tidal effects explain both the morphological evolution of galaxies in distant clusters and the present abundances of distorted disk galaxies in nearby clusters.

Chanamé (PUC), Infante and Reisenegger (PUC) studied the ionized gas kinematics of the LMC-type galaxy NGC 1427 in the Fornax Cluster. This galaxy show an extended pattern of strong star formation. From measured $H\alpha$ velocities they investigate the rotation of the galaxy and argue that the passage through the hot intracluster gas is a very likely scenario to explain its morphological properties.

2.6 Gravitational Lenses

B. Paczyński and his associates worked mostly on a major observing program aimed at detecting gravitational microlensing in the bulge of our Galaxy and in the Magellanic Clouds (the Optical Gravitational Lensing Experiment - OGLE), and the projects that came serendipitously from the OGLE. All hardware and most software was developed by the BP's collaborators at the Warsaw University Observatory, under the leadership of Dr. Andrzej Udalski. The telescope with its CCD camera were in near continuous operation since January 1997, and the data is processed in near real time, i.e. within 24 hours. The results of several observing programs are posted on the WWW at <http://www.astro.princeton.edu/~ogle/> OGLE discovers about 50 microlensing events every year. In the spring of 1999 the first OGLE event towards the LMC was detected, as well as the first event in the Carina region of the Milky Way. Also, in addition to the numerous single events four double lens events with caustic crossing were found last year.

A major new software tool, the image subtraction method was developed by C. Alard and R. H. Lupton using OGLE data. It has been already applied to the near real time photometry of the quadruple quasar 2237+0305 (Huchra's lens) by P. Woźniak, Princeton graduate student. The results are posted on the WWW on a day following the observations, and the paper with data analysis was submitted to ApJ.

Working in collaboration with a substantial number of collaborators at Apache Point Observatory and several other institutions in the US, Australia, Germany and Japan, Turner is continuing the APO gravitational lens photometric monitoring program. Light curves are being accumulated in two bands (g' and r') using the SPICam imager on the APO 3.5-meter telescope at a sampling rate of approximately alternate

nights. These data are used for a variety of purposes including measurement of lens differential time delays, statistical characterization of intrinsic quasar/AGN variability, microlensing studies and potential triggering of spacecraft target-of-opportunity observations of "caustic crossing" events. The latter could lead to indirect mapping of quasar/AGN emission regions on spatial scales as small as one AU.

J.S.B. Wyithe (Visiting Student Research Collaborator from the University of Melbourne), R.L. Webster (U. Melbourne) and Turner have developed a method for computing the probability distribution of microlensed light curve derivatives both in the case of a static lens with a transverse velocity, and in the case of microlensing that is produced through stellar proper motions. The distributions are closely related in form, and can be considered equivalent after appropriate scaling of the input transverse velocity. The comparison of the distributions in this manner provides a consistent way to consider the relative contribution to microlensing (both large and small fluctuations) of the two classes of motion, a problem that is otherwise an extremely expensive computational exercise. They find that the relative contribution of stellar proper motions to the microlensing rate is independent of the mass function assumed for the microlenses, but is a function of optical depth and shear. They also find that stellar proper motions produce a higher overall microlensing rate than a transverse velocity of the same magnitude. This effect becomes more pronounced at higher optical depth. With the introduction of shear, the relative rates of microlensing become dependent on the direction of the transverse velocity. This may have important consequences in the case of quadruply lensed quasars such as Q2237+0305, where the alignment of the shear vector with the source trajectory varies between images.

Wyithe, R.L. Webster (U. Melbourne) and Turner also note that determination of microlensing parameters in the gravitationally lensed quasar Q2237+0305 from the statistics of high magnification events will require monitoring for more than 100 years. However, they have shown that the effective transverse velocity of the lensing galaxy can be determined on a more realistic time-scale through consideration of the distribution of light-curve derivatives. The 10 years of existing monitoring data for Q2237+0305 were analyzed. These data display strong evidence for microlensing that is not associated with a high magnification event. An upper limit of $v_t < 500 \text{ km sec}^{-1}$ is obtained for the galactic transverse velocity which is smaller than previously assumed values. The analysis suggests that the observed microlensing variation may be predominantly due to stellar proper motions. The statistical significance of the results obtained from this method will be increased by the addition of data points from current and future monitoring campaigns. However reduced photometric errors will be more valuable than an increased sampling rate.

Building further on these results, Wyithe, R. L. Webster (U. Melbourne) and Turner have used the observed distribution of light curve derivatives to treat the relative rates of microlensing due to proper motions of microlenses, the orbital stream motion of microlenses and the bulk galactic transverse velocity quantitatively. By demanding that the mi-

cro-lensing rate due to the motions of microlenses in the bulge is the minimum that should be observed they determine lower limits of the average mass of stars and compact objects in the bulge of Q2237+0305. If microlenses in the bulge are assumed to move in an orbital stream the lower limit ranges between 0.005 and $0.023M_{\odot}$ where the systematic dependence is due to the fraction of smooth matter and the size of photometric error assumed. However, if the microlenses are assumed to move according to an isotropic velocity dispersion then a larger lower limit of 0.019 - $0.11M_{\odot}$ is obtained. A significant contribution of Jupiter mass compact objects to the mass distribution of the bulge is therefore unambiguously ruled out in this case.

Wyithe, R. L. Webster (U. Melbourne), Turner and D. J. Mortlock (U. Melbourne) then use the observed duration of a gravitational microlensing high magnification event (HME) in Q2237+0305A to place limits on the dimensions of the quasar continuum source. They obtain both upper and lower statistical limits on the size of the continuum source from the observed HME using determinations of transverse velocity obtained from the published monitoring data. Their calculations take account of the caustic orientation as well as the component of the caustic velocity that results from stellar proper motions. Their determination of source size relies on an assumed event duration of 52 days for HME, and so will be refined when more HMEs are observed. The upper and lower limits on the magnified region of the continuum source are 6×10^{15} and $2 \times 10^{13} \text{ cm}$ respectively (99% confidence). Through consideration of the joint probability for source size and mean microlens mass they find that the mean mass lies between $\sim 0.01M_{\odot}$ and $\sim 1M_{\odot}$ (95% confidence).

Wyithe, R. L. Webster (U. Melbourne) and Turner also note that spectrophotometric observations of the gravitationally microlensed quasar Q2237+0305 during a High Magnification Event (HME) is potentially a very powerful tool for probing the structure of the quasars accretion disc on scales of $\sim 10^{-8}$ arc seconds. In cases where the HME is produced by a single caustic (SHME), microlensing induced changes in the spectrum during the event may be used to directly infer the source intensity profile. Several groups are actively monitoring Q2237+0305 with this goal in mind. It is therefore useful to know how often one can expect to observe a HME. Building on the models and parameter determinations described above, they find that the average SHME rate summed over all images in Q2237+0305 is $1.5 \pm 0.6 - 6.2 \pm 1.3$ events per decade. During the period following a caustic crossing, the event rate in the corresponding image is enhanced by $\sim 50 - 100\%$, and therefore that the overall event rate may be higher during these periods. There is 1 chance in $\sim 4 - 10$ of observing a SHME per observing season. The systematic dependence in these values arises from the different assumptions for smooth matter content, orientation of the galactic transverse velocity and the size of photometric error in the monitoring data. The results support continued monitoring of Q2237+0305 with the aim of obtaining detailed spectroscopic and photometric observations of a SHME.

Wyithe and Turner have considered the temporal smearing of gamma ray bursts due to gravitational microlensing.

Several authors have discussed the utility of using microlensed gamma ray bursts (GRBs) to probe the cosmological population of Massive Compact Halo Objects (MACHOs) by searching for the repeating signals that should result from gravitational lensing by a single mass. However, Wyithe and Turner have considered the microlensing effect on the observed flux of GRBs of a collection of MACHOs. They consider the cumulative flux as a function of time resulting from delays due to microlensing by cosmological MACHOs, and its variation with MACHO mass and optical depth and find that the observation of a number of GRBs that do not exhibit faint echos due to low magnification delayed microimages could be used to place limits on the mass and optical depth of cosmological MACHOs.

W. Colley (Harvard CfA), T. Kundic (Renaissance Tech.) and Turner have completed an analysis of all four years of APO 3.5-meter monitoring data of the gravitational lens system Q0957+561A,B and constructed well sampled light curves in two bands. The differential time delay and image brightness ratio determined from the first two years of data are confirmed and even more accurately measured. The data place strong constraints on the rate of microlensing perturbations affecting the light curves.

B. Pindor (Princeton graduate student) and Turner, working in collaboration with a group of other members of the SDSS collaboration, have begun to search for new gravitational lens systems in the early SDSS imaging data. A large number of promising candidates have been selected on the basis of color and image morphology via a partially automated algorithm. Some of the most promising cases have been followed up with spectroscopy using the APO 3.5-meter telescope, but none have yet been confirmed. A population of compact, intensely star forming galaxies at moderate redshift (0.2 to 0.3) are producing a significant background of false positives.

Yun Wang and Edwin Turner studied the self-lensing of a singular isothermal sphere. Many astrophysical systems can be approximated as isothermal spheres. In an isothermal sphere, the ‘‘foreground’’ objects can act as lenses on ‘‘background’’ objects in the same distribution. They studied gravitational lensing by a singular isothermal sphere analytically. Their results may have interesting applications.

2.7 Gamma-Ray Bursts, Active Galactic Nuclei, and Black Holes

B. Paczyński continued his work on gamma-ray bursts: the relation between the GRBs and supernovae, and the possible observable outcome of neutron star mergers. A mini-review paper on the subject is in preparation.

The OGLE team observed optical afterglow of the GRB 990510 on several nights, and the first very clear evidence of the change of the decay slope was found. All data was made public domain on the WWW, and was used for an overall compilation and analysis by several groups (K. Stanek, *et al.*, and F. Harrison, *et al.*).

Cen proposed a scenario that explains both the observed high pulsar velocities and extragalactic gamma-ray bursts (GRBs). The model involves an ultra-relativistic jet from a supernova (SN), that produces a GRB and its afterglow,

whose characteristics are similar to an isotropic fireball GRB perhaps with some differences at late times in the afterglow once some significant transverse diffusion has occurred. The time scales and many other properties of GRBs and their afterglows in this model are consistent with observations. GRBs in this model have special intrinsic properties, that can either falsify or prove this model unambiguously by observations. The most direct proof is the detection of a SN about the same time as the luminous GRB event. Most GRBs and SNe are expected to occur at moderate redshift ($z \sim 1 - 3$), if they follow the observed universal star formation history, as implied in this model. Searching for GRB/SN associations is a challenge, because the majority of the SNe will be faint.

Cen has shown that differential Doppler shift of different patches of the blastwave front in the fireball model at varying angles to the line of sight could provide an intrinsic smoothing mechanism for the spectra of gamma-ray bursts (GRBs) and the associated afterglows at lower energy bands. For the model parameters of interest, it is illustrated that a monochromatic spectrum at ν in blastwave comoving frame is smoothed and observed to have a half-width-half-maximum (HWHM) of $\sim (0.6 - 2.0)\nu$. Some other implications of this smoothing process are discussed. In particular, if the circumburster medium is uniform and electron and magnetic energies are fixed fractions of the total post-shock energy with time, the observed GRB or afterglow spectra cannot be steeper than $\nu^{-\alpha}$ with $\alpha = 0.75 - 1.25$, regardless of the intrinsic spectra in the comoving shock frame; i.e., a very steep electron distribution function (with $p > 3$) could produce an observed spectrum with $\alpha \sim 1$. In addition, a generic fast-rise-slow-decay type of GRB temporal profile is expected.

Cen has shown the bright, transient companion spot to SN1987A with a projected distance of about 17 light-days, observed by optical speckle interferometry one to two months after explosion, may be due to a receding ultra-relativistic jet traveling at $\sim 53^\circ$ to the observer-to-SN1987A vector, through a circumstellar medium of density profile $\rho(r) \propto r^{-2}$. If it had approached us along the line of sight, a very bright gamma-ray burst would have been seen with an apparent isotropic energy of $\sim 10^{54}$ erg and an opening angle of a few degrees. The model provides an adequate explanation for the evolution of the spot, although there are still problems in explaining its observed color. This model implies that at least some GRBs would be seen as going through a medium with density $\rho(r) \propto r^{-2}$ rather than a uniform medium which is frequently adopted in GRB calculations. Improved analysis of the speckle data has revealed another and fainter spot on the opposite side.

T. Kundic (Renaissance Tech.) and Turner have completed reduction and analysis of the light curves of six gravitational lens systems, including that of Q0957+ 561A,B, monitored during the first four years of the APO 3.5-meter lens monitoring project. These data reveal a striking and tight correlation between the g and r band variability that does not appear to be easily understood in terms of conventional models of AGN accretion disks.

L.-X. Li has considered a toy model for the Blandford-

Znajek mechanism: a Kerr black hole with a toroidal electric current residing in a thin disk around the black hole in the equatorial plane. The electromagnetic power of the black hole and disk is calculated. Li has found that, for a wide range of parameters specifying the rotation of the black hole and the distribution of the electric current in the disk, the power of the disk dominates the power of the black hole. As the disk loses its angular momentum, the mass of the disk gradually drifts towards the black hole and gets accreted. Ultimately the power comes from the gravitational binding energy between the disk and the black hole, as in the standard theory of accretion disk, instead of the rotational energy of the black hole. This suggests that the Blandford-Znajek mechanism may not be effective in extracting rotational energy from a Kerr black hole with a disk.

R. Rafikov (Princeton graduate student), I. Kuznetsova (Moscow Institute of Physics & Technology), and V. Beskin (P.N. Lebedev Physical Institute, Moscow) studied the process of particle acceleration in the strong magnetic field in the vicinity of black holes and neutron stars. This phenomenon is important in understanding the physics of pulsars and AGNs. They considered the stationary axisymmetric outflow from a rotating sphere with a (split) monopole magnetic field. The stream equation describing the outflow is linearized in terms of the Michel magnetization parameter $\sigma^{-1} \ll 1$, which allows a self-consistent analysis of the direct problem. It is shown that for a finite σ the fast magnetosonic surface is located at a finite distance $\sim \sigma^{1/3}R_L$ ($R_L = c/\Omega_F$ is the light cylinder). They have also found that the particle energy at the fast surface is just equal to the value $\gamma \sim \sigma^{1/3}$. The particle acceleration and magnetic field collimation are shown to become ineffective outside the fast magnetosonic surface.

Fan and Strauss, in collaboration with a large number of astronomers in Princeton and the Sloan Digital Sky Survey consortium, have carried out a spectroscopic survey of high-redshift quasar candidates based on early SDSS imaging data, and guided by Fan's models mentioned above. As of this writing, they have discovered over 30 quasars with redshifts greater than 3.6, including two with redshift greater than 5. They have also discovered a number of objects with very unusual spectra, including a $z=4.6$ object without emission lines, a $z=4.90$ BAL quasar, and two objects whose spectra defy classification.

There is strong evidence that some kind of massive dark object is present in the centers of many nearby galaxies. The detection of flares from tidally disrupted stars could confirm that these objects are black holes (BHs). Tremaine and J. Magorrian (CITA and Cambridge) have computed stellar disruption rates in detailed dynamical models of real galaxies, taking into account the refilling of the loss cone of stars on disruptable orbits by two-body relaxation, and by tidal forces in non-spherical galaxies. The highest disruption rates (one star per 10^4 yr) occur in faint ($L < 10^{10}L_\odot$) galaxies, which have steep central density cusps. More luminous galaxies are less dense and have much longer relaxation times and more massive BHs. Dwarf stars in such galaxies are swallowed whole by the BH and hence do not emit flares; giant stars could produce flares as often as every 10^5 yr,

although the rate depends sensitively on the shape of the stellar distribution function. Such flares could be detected in current supernova searches. The total mass of stars consumed over the lifetime of the galaxy is of order $10^6 M_\odot$, independent of galaxy luminosity; thus disrupted stars may contribute significantly to the present BH mass in galaxies fainter than $\sim 10^9 L_\odot$.

2.8 Galaxies

Tremaine has studied the geometry of the structures in galaxies that arise through incomplete phase mixing. These structures occupy a complex surface of dimension D in six-dimensional phase space, where usually $D \leq 3$ (e.g. $D = 1$ for tidal tails). The appearance of such structures to observers is determined by their projection into a space whose dimensionality K is determined by the number of observables in the survey (e.g. sky position, distance, radial velocity, etc.). The most prominent features in surveys with $K \geq D$ and incomplete phase mixing will be stable singularities (catastrophes). The simplest of these are the shells seen in the outer parts of elliptical galaxies, which are examples of fold singularities; more complicated singularities can arise but for $D \leq 3$ they fall into only a few categories: folds, cusps, swallowtails, elliptic and hyperbolic umbilics.

M. Vogeley began an analysis of statistical fluctuations in the background light as measured in the Hubble Deep Field South after masking out detected galaxies. This measurement will strongly constrain possible sources of the optical extragalactic background light. This constraint is crucial for determining the spectrum of the EBL because reported upper limits on the optical EBL are several times larger than the surface brightness from detected galaxies, suggesting the possibility of additional galaxy populations. Vogeley's previous analysis of the HDF North indicated that the mean optical EBL is likely to be within a small fraction of the surface brightness from detected galaxies. Analysis of the HDF South provides a test of this result in an independent area on the sky.

M. Vogeley, with J. Huchra and M. Geller (CfA), published the South Galactic Cap region of the extension of the Center for Astrophysics redshift survey to magnitude $m_{z,w} \leq 15.5$.

To study the multicolor photometric properties of bright galaxies, M. Vogeley, Z. Ivezić, and undergraduate K. Finlator matched the Updated Zwicky Catalog (Falco, *et al.* 1999) with five-band driftscan photometry from the SDSS. This matching also provides a critical test of the SDSS photometry software itself.

M. Strauss and M. Vogeley were responsible for testing the algorithms that select galaxies from SDSS photometry as targets for SDSS spectroscopy. M. Vogeley was responsible for producing documentation to support testing of data from the SDSS imaging camera.

2.9 Galactic Astronomy and Interstellar Matter

H. Zhao, K. Johnston, L. Hernquist and D. Spergel have continued their investigations of tidal debris as a probe of the galactic potential. Future astrometric satellites, such as SIM

(NASA's Space Interferometric Mission) and GAIA (ESA's Global Astrometric Interferometer for Astrophysics), hold the promise of mapping out the detailed phase space structure of the Galactic halo by providing unprecedented annual proper motion and parallax of $1 - 10 \mu\text{as}$ astrometric accuracy. They show that proper motions of hundred or so giant branch stars in tidal debris torn from a small satellite (a $10^{5-7} L_\odot$ Galactic dwarf galaxy or globular cluster) in the halo is sensitive to the current Galactic potential and its past evolution. They follow the evolution of a cold (velocity dispersion of 10 km/s) stream on a nearby (between 8-50 kpc) polar orbit in a variety of histories of the potential of the Galaxy, and observe the bright ($V < 18\text{mag}$) members of the debris tail with GAIA accuracy. They simulate effects due to the growing or flipping of the Galactic disk over the past 4 Gyrs or the perturbation from a massive accreted lump such as the progenitor of the Magellanic Clouds. They study various factors influencing their ability to identify streams, including contamination from field stars, accuracy of radial velocity and distance data and evolution and non-axial symmetry of the potential. Their simulations suggest that nearby, cold streams could be detected with GAIA if these cousins of the Sagittarius stream exist. Results of Johnston, Zhao, Spergel and Hernquist (1999) and Helmi, Zhao and de Zeeuw (1999) for static Galactic potentials are likely to be largely generalizable to moderately time-evolving potentials. SIM and GAIA measurements of debris stars might be used to probe both Galactic structure and Galactic history.

Draine has continued to work on theoretical astrophysics of the interstellar medium, with particular attention to problems connected with (1) emission and absorption of electromagnetic radiation by interstellar dust grains; (2) the dynamics of interstellar dust grains, particularly in connection with the problem of grain alignment; (3) the physics of photodissociation fronts; (4) the expected rates of accretion of metal atoms onto interstellar grains, and whether the observed interstellar depletions are consistent with their understanding of the kinetics; and (5) the possibility that a proposed population of very small interstellar clouds might be observed through the phenomenon of "gaseous lensing" of light from distant stars.

ISO observations of the planetary nebula NGC 2346 were modelled in terms of a propagating ionization/dissociation front (Vicini, *et al.* 1999). The H_2 line emission was modeled using the UV pumping/collisional excitation-dissociation code developed by Draine.

Draine & Lazarian (1998) studied the rotational dynamics of dust grains and found that very small grains could attain rotation rates as high as 100 GHz, and that the small grain population would be expected to radiate electric dipole emission with intensities and spectrum capable of accounting for the "anomalous" microwave emission which several groups have previously discovered to be correlated with $100 \mu\text{m}$ emission from interstellar dust, and the physical processes involved in the rotational dynamics are discussed – important processes include rotational damping by rotational electric dipole radiation as well as by emission of infrared photons following heating by absorption of starlight photons, and rotational excitation by collisions with atoms and ions.

Even in predominantly neutral regions, ions play an important role in rotational excitation because of electrostatic focussing effects. The intensity of the rotational emission has been estimated for various interstellar environments.

Draine & Lazarian (1999) examined the physics of thermal fluctuations of the magnetization within interstellar grains, and show that if the iron in interstellar grains resides in ferrimagnetic or ferromagnetic materials, there can be strong magnetic dipole radiation in the microwave region resulting from thermal fluctuations. In fact, observations near 90 GHz can be used to show that not more than approximately 5% of interstellar Fe can be in metallic form.

Lazarian and Draine (1999) showed that thermal fluctuations within interstellar grains can have profound effects on the grain dynamics of dust grains undergoing “crossovers,” where the grain rotation (in body coordinates) is undergoing a reversal. Dissipation associated with the Barnett effect will result in a phenomenon which Lazarian and Draine term “thermal flipping,” where the effect of the fluctuation is to accelerate the “flipover” which the grain must undergo as the result of the torques which will produce first a spin-down followed by a spin-up (with the grain rotation reversed in body-coordinates).

Graduate student Joseph Weingartner and Draine have investigated the expected rates for depletion of metal atoms onto dust grains in various phases of the interstellar medium. Weingartner and Draine (1999) show that the observed depletions can in fact be understood provided the bulk of depletion takes place in dense clouds; this requires rapid exchange of matter between the dense phases (where depletion can take place) and the diffuse phases (where we are able to measure depletions via ultraviolet absorption line studies).

Draine (1998) pointed out that the dust-free gas clouds which have been proposed as a “dark matter” component of the Galaxy could be detectable through their lensing effects on background stars. If a significant fraction of the gravitational mass of the Galaxy were contained in a halo population of Jovian-mass cold clouds, they could be detected through their contribution to lensing of stars in the LMC and SMC. The light curves closely resemble “gravitational lensing” light curves in the high-magnification region, but demagnification also is present (unlike gravitational lensing). Accurate photometry by existing programs to study microlensing could strongly constrain the cloud population. The hypothesized clouds could be definitively detected during a gaseous lensing event by observation of far-red absorption lines of H₂ in the stellar spectrum.

The analysis of data from the Interstellar Medium Absorption Profile Spectrograph (IMAPS) which flew on the ORFEUS-Spas II Shuttle mission in late 1996 is continuing. Most of the effort by E. Jenkins, T. Tripp, P. Woźniak (graduate student), G. Sonneborn (NASA GSFC), and U. Sofia (Whitman College) has focused on careful measurements of the deuterium-to-hydrogen ratios for interstellar matter in the directions toward δ Ori, ζ Pup and γ^2 Vel. The results seem to provide an abrupt reversal of the general notion that D/H is the same everywhere in the local part of the Galaxy. Toward δ Ori A they found that $N(\text{D I})/N(\text{H I}) = 7.4_{-1.3}^{+1.9} \times 10^{-6}$ at a 90% confidence

level. By contrast, for γ^2 Vel $N(\text{D I})/N(\text{H I}) = 2.12 \pm 0.35 \times 10^{-5}$, a value that is about three times larger. The determination for ζ Pup gives $N(\text{D I})/N(\text{H I}) = 1.67 \times 10^{-5}$ which is close to determinations for the very local medium revealed by HST observations of absorption against the chromospheric emission of late-type stars.

P. Woźniak has carried out a detailed analysis of the H₂ lines appearing in the IMAPS spectra of ϵ and δ Ori, to see if they repeat the unusual shifts and broadening for lines coming out of different levels of rotational excitation that was reported earlier for ζ Ori A, only 1 to 2 degrees away in the sky, by E. Jenkins & A. Peimbert (former graduate student). Apparently the features toward these two stars do not exhibit this bizarre behavior, which is perhaps not unexpected since there is no high velocity atomic gas that could create the shock needed to explain the broadening and velocity shifts for different J .

Extending previous work of B.T. Draine and A. Lazarian, postdoctoral research associate A. Li and B.T. Draine are studying the rotational dynamics of ultrasmall interstellar grains. Because the excitation occurs in a system which is far from equilibrium, the rotational distribution function will deviate, perhaps significantly, from a Maxwellian. Detailed modelling of the excitation and damping processes allows calculation of the steady-state rotational distribution function, and from this the microwave emission spectrum is calculated. It is found that the resulting emission spectrum can deviate substantially from emission spectra which had previously been calculated using a Maxwellian distribution function.

A. Li, J.M. Greenberg (Leiden) and D.H. Wooden (NASA-Ames) have been working on comet Hale-Bopp. Modeling the near infrared silicate emission spectra together with the submillimeter continuum as a function of heliocentric distance, they seek to constrain the coma dust mineralogy, dust and gas production rate, as well as the nucleus morphology of Hale-Bopp.

E. Jenkins and T. Tripp are collaborating with C. Bowers (NASA GSFC), F. Roesler, R. Reynolds and M. Haffner (U. Wisc.) in observing the spectra of 21 stars over the wavelength intervals 1160 to 1361 Å and 1626 to 1906 Å to register interstellar absorption features using the STIS instrument on HST. The primary objective of this program is to sample the thermal pressures of the interstellar medium by measuring the relative populations of neutral carbon atoms in excited fine-structure levels. Secondary objectives include the detection of H II regions with the excited Si II line and the measurements of various atomic abundances. The narrowest features detected so far indicate that the use of a special, narrow entrance slit on STIS and a half-pixel sampling of the MAMA detector allows one to attain a wavelength resolving power $\lambda/\Delta\lambda = 200,000$ with the highest resolution echelle gratings. Most of the targets were chosen to be within HST’s continuous viewing zone, so that a factor two efficiency gain in observing could be attained. As a result, most targets in the plane of the galaxy are centered about the galactic longitudes 120° and 300°. A few stars were selected at high galactic latitudes so that useful comparisons could be made with results from the Wisconsin H

Alpha Mapper (WHAM).

2.10 Stellar Systems

Several new catalogs were published by the OGLE: 1459 eclipsing binaries in the SMC, and double mode and second overtone cepheids in the SMC. A catalog of about half a million photometric measurements of several thousand cepheids in both Magellanic Clouds is in preparation, and should be available on the WWW by the end of summer, 1999.

P. Woźniak and M. Szymański analyzed stellar variability background which may be confused with small amplitude microlensing events. There is fortunately not much danger of contamination, provided care is taken about establishing non-variability of the lens candidate outside of the lensing time interval.

A major result of the OGLE project is the establishment of red clump giants as one of the best standard candles currently available. In order to clarify a confusion about the color - metallicity relation B. Paczyński and the rest of the OGLE team are preparing a catalog of several hundred red clump giants in Baade's Window with extinction corrected U, B, V, I photometry, to be used as a finding list by spectroscopists. Red clump giants offer a better alternative to M giants for bias free studies of metallicity distribution in the galactic bulge stars. It is expected that future spectroscopic metallicities will correlate well with the colors, and will increase the confidence with which red clump giants can be used to estimate distances.

A potentially more accurate way to measure distance to the Magellanic Clouds is to use detached, eclipsing spectroscopic binaries. This approach has been successfully attempted by E. Guinen, *et al.* and corrected by A. Udalski, *et al.* using the binary HV 2274. The availability of a large number of very 'clean' eclipsing systems discovered by OGLE will lead to a considerable improvement in the accuracy of the LMC and SMC distance determinations.

At this time all OGLE results point strongly to the 'short' distance scale, with the distance modulus $(m - M)_{LMC}$ in the range 18.2 - 18.3, distinctly smaller than the distance adopted by the HST Key project, but in agreement with the implications of cepheids found in the NGC 4258, the galaxy with the accurate maser distance. If the 'short' distance scale turns out to be correct, then H_0 based on cepheids and SN Ia will have to be increased by 10-15%.

A project which evolved from OGLE, the search for detached eclipsing binaries in globular clusters is led by J. Kaluzny, visiting Princeton from the Warsaw University Observatory, and conducted in collaboration with I. Thompson of the Carnegie Institution of Washington. At least half a dozen binaries of the right type have been found in several globular clusters, and OGLE-V-17 in Omega Cen has its first spectroscopic orbit determined. The masses and radii of the two components, both close to the main sequence turn-off point, are $M_2 = 0.78 \pm 0.08M_\odot$, $R_2 = 1.85 \pm 0.10R_\odot$, $M_1 = 0.68 \pm 0.07M_\odot$, $R_1 = 0.86 \pm 0.05R_\odot$. The accuracy is limited by the small photon collecting area of the telescopes used. With the Magellan

and/or VLT it will be possible to reduce the errors and to determine accurate distance, age and helium content.

Gnedin and Ostriker study the reaction of a globular star cluster to a time-varying tidal perturbation (gravitational shock) using self-consistent N-body simulations and address two questions. First, to what extent is the cluster interior protected by adiabatic invariants? Second, how much further energy change does the postshock evolution of the cluster potential produce and how much does it affect the dispersion of stellar energies? They introduce the "adiabatic correction" as the ratio of the energy change, $\langle dE \rangle$, to its value in the impulse approximation. When the potential is kept fixed, the numerical results for the adiabatic correction for stars with orbital frequency Ω can be approximated as $(1 + \Omega^2 \tau^2)^{-\gamma}$.

For shocks with the characteristic duration of the order of the half-mass dynamical time of the cluster, $\tau < t_{dyn,h}$, the exponent $\gamma = \frac{5}{2}$. For more prolonged shocks, $\tau > 4t_{dyn,h}$, the adiabatic correction is shallower, $\gamma = \frac{3}{2}$. When they allow for self-gravity and potential oscillations that follow the shock, the energy of stars in the core changes significantly while the total energy of the system is conserved. Paradoxically, the postshock potential fluctuations reduce the total amount of energy dispersion, $\langle dE^2 \rangle$. The effect is small but real and is due to the postshock energy change being statistically anticorrelated with the shock-induced heating. These results are to be applied to Fokker-Planck models of the evolution of globular clusters.

Gnedin and Ostriker, in collaboration with L. Hernquist (Santa Cruz), derive expressions for the tidal field exerted by a spherically symmetric galaxy having an extended mass distribution and use their analysis to calculate tidal heating of stars in a globular cluster or a satellite galaxy. They integrate the tidal force over accurate orbits in various models for the primary by using the impulse approximation, coupled with adiabatic corrections that allow for time variation of the perturbation. They verify the results with direct N-body simulations, and they also compare them with the conventional straight-path approximation. Heating on highly eccentric orbits dominates, since adiabatic corrections strictly prohibit energy changes on low-eccentricity orbits. The results were illustrated for globular cluster NGC 6712. For the orbital eccentricities higher than 0.9, the future lifetime of NGC 6712 is less than 10^{10} yr. Their analysis can be used to study tidal interactions of star clusters and galaxies in a semianalytical manner.

Gnedin and Ostriker, in collaboration with H.M. Lee (Seoul Nat. Univ., Korea), present new Fokker-Planck models of the evolution of globular clusters, including gravitational tidal shocks. They extend their calculations beyond core collapse by adopting three-body binary heating. Effects of the shocks are included by adding the tidal shock diffusion coefficients to the ordinary Fokker-Planck equation: the first order heating term, $\langle dE \rangle$, and the second order energy dispersion term, $\langle dE^2 \rangle$. As an example, they investigate the evolution of models for the globular cluster NGC 6254. Using the Hipparcos proper motions, they are now able to construct orbits of this cluster in the Galaxy. Tidal shocks accel-

erate significantly both core collapse and the evaporation of the cluster and shorten the destruction time from 24 Gyr to 18 Gyr. They examine various types of adiabatic corrections and find that they are critical for accurate calculation of the evolution. Without adiabatic corrections, the destruction time of the cluster is twice as short. They examine cluster evolution for a wide range of the concentration and tidal shock parameters, and determine the region of the parameter space where tidal shocks dominate the evolution. They present fitting formulae for the core collapse time and the destruction time, covering all reasonable initial conditions. In the limit of strong shocks, the typical value of the core collapse time decreases from $10 t_{rh}$ to $3 t_{rh}$ or less, while the destruction time is just twice that number. The effects of tidal shocks are rapidly self-limiting: as clusters lose mass and become more compact, the importance of the shocks diminishes. This implies that tidal shocks were more important in the past.

2.11 Stars

Ž. Ivezić and G. Knapp, in collaboration with T. Knauer (U. Kentucky), studied about 12,000 stellar sources observed in both the IRAS and HIPPARCOS Surveys. They calculate bolometric luminosities from the integrated spectral energy distributions from the UV to far-IR wavelengths and the HIPPARCOS parallaxes. For about 2,000 sources with the best data (error in luminosity of less than 50%) they perform a detailed analysis of the spectral properties, and correlations between the luminosity and dust emission. They use the IRAS [25]-[12] color to select sources with dust emission and show that they are found throughout the Hertzsprung-Russell diagram, including pre-main-sequence, main sequence, and post-main-sequence objects. Ivezić, Knapp and Knauer also find clear evidence that M and N stars with dust emission have luminosities 3-4 times larger than their counterparts without dust. They estimate a minimum threshold luminosity of about $2000 L_{\odot}$ for evolved stars to have dust, in good agreement with models for radiatively driven winds. Once this threshold is achieved, the amount of circumstellar dust seems to be independent of the stellar luminosity.

Ž. Ivezić, in collaboration with D. Vinković, M. Elitzur (U. Kentucky) and A. Miroshnichenko (Pulkovo Obs.) has continued to work on the studies of medium- and high-mass young stellar objects. They have developed a radiative transfer code to model continuum emission from an optically thick and geometrically thin disk embedded in a spherical envelope. Ivezić and collaborators fit their models to infrared spectral energy distributions and infrared imaging data for a sample of Herbig Ae/Be stars. They show that these models overcome difficulties encountered in previous studies, in particular the puzzle of observed sizes decreasing with wavelength. Such a decrease is found to be a consequence of the disk emission overtaking envelope emission: the disk temperature decreases much faster with radius than the envelope dust temperature, hence the effective size for disk emission is smaller than for envelope emission.

Graduate student Xiaohui Fan has published a detailed theoretical study of the distribution of stellar objects in the color space of the Sloan Digital Sky Survey, modelling or-

dinary stars, white dwarfs, quasars, and compact emission-line galaxies.

With its deep magnitude limit (about 23 for the more sensitive bands), excellent image quality and very accurate photometry, it was expected that the SDSS would be a goldmine for the study of very cool stars. This has indeed turned out to be the case with the discovery in the first SDSS test imaging data of several spectroscopically confirmed ‘L’ dwarfs (the next spectral class below M dwarfs) and the first field ‘methane’ dwarfs - objects like G1229B which are cool enough (< 1000 K) to have atmospheric methane bands, i.e. to have spectra very like those of the giant gas planets, Jupiter and Saturn. The discovery of these objects has blurred the distinction between stars and planets, and shown that objects of masses at most a few tens times that of Jupiter can form alone. The ‘L’ dwarfs may or may not be brown dwarfs - the methane dwarfs certainly are. A large number of candidate L dwarfs have been identified in SDSS commissioning data (including many objects with ‘L dwarf’ colors in the NGC 2068/NGC 2071 star forming region in Orion). Spectroscopy with the ARC 3.5 m telescope of some of these objects shows that they range in spectral type from L0 to L8. The detection rate of candidate objects is about 1 per 15 square degrees, and the SDSS is expected to find many thousands of them. They were found in the SDSS photometric data by their distinctive r-i and i-z colors, and their spectra were taken with the APO 3.5 meter telescope. The first SDSS methane dwarf was found by X. Fan and M. Strauss, and confirmed with near-infrared spectra taken at UKIRT by S. Leggett (UKIRT) and T. Geballe (Gemini). The second was found by Z. Tsvetanov, W. Zheng and D. Golimowski (JHU). Ten ‘SDSS’ L dwarfs have been found by the above groups and by D. Schneider (Penn State), who used the Hobby-Eberly telescope. SDSS collaborators in this effort include J. Gunn, R. Lupton, Z. Ivezić, G. Knapp and J. Pier.

Knapp, Ivezić, Ken Young (CfA) and Merce Crosas (CfA) carried out a search for atomic carbon in the envelopes of evolved stars using the Caltech Submillimeter Observatory (CSO). Atomic carbon was detected in the envelopes of three carbon-rich evolved stars: HD 44179 (AFGL 915, the ‘Red Rectangle’); HD 56126; and, tentatively, the carbon star V Hya. This brings to seven the number of evolved star envelopes in which CI has been detected. Upper limits were found for several other stars, including R CrB. CI was not detected in several oxygen rich post asymptotic giant branch (AGB) stars (OH231.8+4.2, for example), although it is detected in their carbon-rich analogues. Two trends are evident in the data. First, circumstellar envelopes with detectable CI are overwhelmingly carbon rich, suggesting that much of the CI is produced by the dissociation of molecules other than CO. Second, the more evolved the envelope away from the AGB, the higher is the CI/CO ratio. The oxygen-rich supergiant star α Ori remains the only oxygen rich star with a wind containing detectable CI.

These data suggest an evolutionary sequence for the CI/CO ratio in cool circumstellar envelopes. This ratio is small (a few %) while the star is on the AGB, and the CI is located in the outer envelope and produced by photodissociation. The ratio increases to about 0.5 as the star evolves

away from the AGB because of the dissociation of CO and other carbon-bearing molecules by shocks caused by the fast winds which appear at the end of evolution on the AGB. Finally, the ratio becomes $\gg 1$ as the central star becomes hot enough to photodissociate CO.

Several examinations of the structure of the circumstellar envelopes around nearby individual evolved stars were carried out. Knapp, Crosas, Young and Karl Menten (Max Planck Institut) made observations of submillimeter spectral line emission from the molecular envelope of Mira with the CSO. Several rotational lines of ^{12}CO and ^{13}CO (up to $J = 6-5$) and of SiO (up to $J = 16-15$) were observed. The profiles show bright emission at the stellar velocity probably associated with a circumstellar envelope expanding at $2 - 3 \text{ km s}^{-1}$, plus blue and redshifted wings which may be due to a bipolar outflow. The wings are asymmetric: both the ^{12}CO and ^{13}CO lines show brighter blueshifted emission, while the SiO lines show brighter redshifted emission. Three models were explored: a) a bipolar outflow, b) a binary system, in which Mira moves with a velocity around its companion which is similar to the outflow velocity of the envelope, and c) an edge-on, dense, disk in which the ^{13}CO line is also optically thick. All three models can qualitatively reproduce most of the features of the observed line profiles, if additional conditions are applied. However, the binary model provides the most natural reproduction of all the features of the observed ^{12}CO , ^{13}CO , and SiO emission.

Knapp, Young and Crosas observed the envelope of the S star π Gru in the CO($J = 2-1$) and SiO($J = 5-4$) lines. The CO line profile differs from the usual parabolic shape seen in uniformly-expanding envelopes; it has a Voigt-like profile and two horns. A model for line formation in the envelope shows that a tilted, expanding disk reproduces the observations well. The star also has a fast molecular wind, with a projected outflow speed of at least 70 and perhaps as high as 90 km s^{-1} . The fast wind is presumably ejected from the poles of the disk.

Knapp, S. Dobrovolskii (Princeton graduate student), Ivezić, Young, Crosas, J. Mattei (AAVSO) and M. Rupen (NRAO) also studied the carbon star V Hya. This star has two variability periods, 530^{d} and 6000^{d} (17 years) which have been observed for more than 100 years and have been regular over this time. The 530^{d} period and its $1.5^{\text{m}} - 2^{\text{m}}$ amplitude show that V Hya is a Mira variable. These authors suggest that the star is in a binary system (as also suspected from the structure of the circumstellar envelope) and that the 17-year variation is due to extinction by circumstellar dust orbiting with the companion. The properties of the envelope found from molecular line observations: the fast molecular wind, the relatively small size of the dense circumstellar envelope, and the high mass loss rate, all suggest that V Hya has entered its ‘superwind’ phase. However, its spectral type, period, colors, and lack of ionizing radiation show that the star is still on the AGB. These observations of V Hya and π Gru show that the complex structure seen in many planetary nebulae, including quadrupolar structure and fast winds, may largely evolve from structure formed while the progenitor star is in the last stages of evolution on the AGB.

Motivated by the surprising torque behavior observed in

accreting X-ray pulsars, Robert Nelson is completing a study of the interaction between an accretion disk and a rotating stellar magnetosphere. In particular, he has generalized the Weber-Davis model of angular momentum transport in the solar wind to include both viscous and magnetic dissipation. The inner disk boundary layer is a transition region where angular momentum transport switches from viscous to magnetic stresses. The torque acting on the star is an eigenvalue of the MHD equations; it must be determined by solving the fluid motion and field structure self-consistently. As has been shown for purely fluid star-disk boundary layers, the star can spin down while continuing to accrete material. This may explain the dramatic spin-up/spin-down states observed in accreting X-ray pulsars.

Anticipating the launch of the Chandra X-ray telescope, Robert Nelson and Graduate Student Lei Hao are exploring mechanisms of X-ray emission from pre-main sequence stars (PMS). These rapidly rotating and fully convective stars are known to produce outbursts of X-ray and radio emission comparable to their time-averaged bolometric luminosities. It is unclear if these outbursts are due to star-disk interactions, or are intrinsic to magnetic activity of the stars themselves. They are attempting to clarify potential Chandra observations that could distinguish between these physical models. Borrowing from empirical studies of X-ray emission from main sequence stars, they are exploring the dependence of X-ray luminosity on the effective Rossby number describing the convective PMS stellar interior.

2.12 Planets and Proto-Planets

Tremaine has investigated the process of resonant relaxation, a novel form of gravitational relaxation that arises in nearly Keplerian disks such as protoplanetary disks. Resonant relaxation does not affect the semimajor axes of the particles, but enhances relaxation of particle eccentricities and inclinations. The equilibrium state after resonant relaxation is a Rayleigh distribution, with the mean-square eccentricity and inclination inversely proportional to mass. The rate of resonant relaxation depends strongly on the precession rate of the disk. If precession due to the disk’s self-gravity is small compared to the total precession, then the relaxation is concentrated near the secular resonance between each pair of interacting bodies; on the other hand if the precession rate is dominated by the disk’s self-gravity then relaxation occurs through coupling to the large-scale low-frequency $m = 1$ normal modes of the disk. Depending on the disk properties—especially the mean-square eccentricity—resonant relaxation may be either stronger or weaker than the usual non-resonant relaxation: for the terrestrial planets, non-resonant relaxation dominates in the early stages of planetesimal growth, but resonant relaxation may dominate in the late stages when the mean-square eccentricity is higher.

Plutinos are Kuiper-belt objects that share the 3:2 Neptune resonance with Pluto. Graduate student Q. Yu and Tremaine have investigated the long-term stability of Plutinos under the combined influence of Neptune and Pluto. Plutinos with eccentricities close to Pluto (fractional eccentricity difference $\Delta e/e_p = |e - e_p|/e_p \lesssim 0.1$) can be stable

because the longitude difference librates, in a manner similar to the tadpole and horseshoe libration in coorbital satellites. Plutinos with $\Delta e/e_p \gtrsim 0.3$ can also be stable; the longitude difference circulates and close encounters are possible, but the effects of Pluto are weak because the encounter velocity is high. Orbits with intermediate eccentricity differences are likely to be unstable over the age of the solar system, in the sense that encounters with Pluto drive them out of the 3:2 Neptune resonance and thus into close encounters with Neptune. This mechanism may be a source of Jupiter-family comets. Despite its tiny mass, Pluto plays a central role in sculpting the present structure of the Kuiper belt.

Tremaine and N. W. Evans (Oxford) have studied multi-step methods for the integration of ordinary differential equations that describe reversible dynamical systems, with particular emphasis on the planar Kepler problem. It has previously been shown by Cano & Sanz-Serna that reversible linear multisteps for first-order differential equations are generally unstable. Evans and Tremaine report on a subset of these methods—the *zero-growth methods*—that evade these instabilities. They provide an algorithm for identifying these rare methods, and find and study all zero-growth, reversible multisteps with six or fewer steps. This select group includes two well-known second-order multisteps (the trapezoidal and explicit midpoint methods), as well as three new fourth-order multisteps—one of which is explicit. Variable timesteps can be readily implemented without spoiling reversibility. Tests on Keplerian orbits show that these new reversible multisteps work well on orbits with low or moderate eccentricity, although at least 100 steps/radian are required for stability.

Symplectic integration algorithms are well-suited for long-term integrations of Hamiltonian systems because they preserve the geometric structure of the Hamiltonian flow. However, this desirable property is generally lost when adaptive timestep control is added to a symplectic integrator. Tremaine and graduate student M. Preto have found an adaptive-timestep symplectic integrator that can be used if the Hamiltonian is the sum of kinetic and potential energy components and the required timestep depends only on the potential energy (e.g. test-particle integrations in fixed potentials). In particular, they describe an explicit, reversible, symplectic, leapfrog integrator for a test particle in a near-Keplerian potential; this integrator has timestep proportional to distance from the attracting mass and has the remarkable property of integrating orbits in an inverse-square force field with only “along-track” errors; i.e. the phase-space shape of a Keplerian orbit is reproduced exactly, but the orbital period is in error by $O(N^{-2})$, where N is the number of steps per period.

The orbit of Neptune’s satellite Nereid has a number of unusual features. Its eccentricity of 0.751 is far larger than the eccentricity of any other planet or satellite in the solar system; it is strongly perturbed by the Sun (the fractional strength of the solar perturbation is only larger for the Moon and a few of the outer satellites of the giant planets); and it is strongly perturbed by Triton. Tremaine and undergraduate student R. deSimone have therefore integrated the orbit of Nereid for 2 Myr. The orbital elements exhibit oscillations with a wide range of timescales but the eccentricity and in-

clination vary by only ± 0.013 and $\pm 4^\circ$ respectively. There is no evidence of chaos on Myr timescales.

Bart Pindor (Princeton graduate student) and Goodman have re-examined the formation of planetesimals in the later phases of a gaseous protoplanetary disk. If planets are to be formed, it is necessary that solid particles segregate themselves from the gas before the gas is removed. It is believed that the particles settle into a relatively dense “dust layer” near the disk midplane, but that turbulence created by the small difference in orbital velocity between the dust layer and the gas prevents the layer from directly achieving a density above the Roche limit for gravitational fragmentation. Pindor and Goodman find, however, that the turbulent drag between the dust and gas has its own rapid instabilities, which concentrate the dust into dense rings with a radial width comparable to the dust-layer thickness. Gravitational fragmentation then becomes possible, and asteroid-sized bodies are expected to result.

Erick Lee (Princeton graduate student) and Goodman studied single-armed spiral waves in gaseous disks whose potential is dominated by a central mass but whose self-gravity is not entirely negligible. Such disks exist around protostars and also around massive black holes in some galactic nuclei. Single-armed waves have a special status in such disks because the gas streamlines are close to elliptical keplerian orbits. This means that the waves can be sustained by very weak pressure and self-gravity, and also that the waves can propagate from large radial distances down to the immediate environment of the central mass. It also makes the construction of nonlinear solutions relatively easy. By variational methods, Lee and Goodman find the *nonlinear* dispersion relation, angular momentum flux, and propagation velocity of tightly-wound waves. The pitch angle increases with amplitude until the tight-winding approximation breaks down. By semianalytic methods, they find a series of nonlinear logarithmic spirals which is exact in the limit of small disk mass and which extends to large pitch angle. A paper describing this work has been accepted for publication in *Monthly Notices*.

N. Wyn Evans (Oxford) and Goodman studied scale-free disks that have no preferred length or time scale. The question has been raised whether such disks have a continuum of unstable linear modes or perhaps no unstable modes at all. They resolve this paradox by analysing the particular case of a gaseous, isentropic disk with a completely flat rotation curve (the Mestel disk) exactly. The heart of the matter is this: what are the correct boundary conditions to impose at the origin or central cusp? They argue that the linear stability problem is ill-posed and that similar ambiguities may afflict general disk models with power-law central cusps. From any finite radius, waves reach the origin after finite time but with logarithmically divergent phase. Instabilities exist, but their pattern speeds depend upon an undetermined phase with which waves are reflected from the origin. For any definite choice of this phase, there is an infinite but discrete set of growing modes. The ratio of growth rate to pattern speed is independent of the central phase. This ratio is derived in closed form for non self-gravitating normal modes and is shown to agree with approximate results obtained from the

shearing sheet in the short-wavelength limit. *This provides the first exact, analytically solved stability analysis for a differentially rotating disk.* For self-gravitating normal modes, the ratio of growth rate to pattern is found numerically by solving recurrence relations in Mellin-transform space. A paper describing this work has been submitted to *Monthly Notices*.

2.13 Plasma Astrophysics

A longstanding problem in the theory of the propagation of cosmic rays is how do the particles pitch angle scatter through 90 degrees. The difficulty is that the hydrodynamic magnetic waves that interact resonantly with cosmic rays with pitch angle θ near 90 degrees have nearly zero wave length and are hard to excite. The question is how does this effect the result that cosmic rays generally have a bulk velocity near the Alfvén speed?

Gian Marco Felice, a PhD student, and Kulsrud have re-examined this problem. They found that the Alfvén waves are themselves scattered through small angles α about the mean magnetic field by nonlinear processes. For those waves resonant with 90 degree cosmic rays, $\mu = \cos\theta \ll 1$ the value of $k_{\perp}\rho \approx \theta/\mu$ can be quite large even for small α , where k_{\perp} is the perpendicular wave number and ρ is the gyration radius. This leads to strong suppression of the growth rate of the waves by the cosmic ray anisotropy and thus the nonlinear damping dominates so the effective damping of the waves is much larger than supposed from standard quasilinear theory. Also, the efficiency of cosmic ray scattering, by the waves is strongly reduced. On the other hand, a large value of $k_{\perp}\rho$ makes the non resonant non linear scattering more effective so it is comparatively easy for this scattering to nonlinearly take the cosmic ray through 90 degrees. They are matching these two processes together to determine the effective drift velocity of cosmic rays through a plasma. They expect it to be considerably larger than the Alfvén speed. This could have nontrivial implications for cosmic ray shock acceleration, as well as cosmic ray propagation through the interstellar medium.

R. Rafikov (graduate student) and A. Gurevich and K. Zybín (P.N. Lebedev Physical Institute, Moscow) carried out the study of magnetohydrodynamic flow of supersonic plasma flux around conductive body. This problem is important in the study of flow of solar wind around planets or the motion of satellites in rarefied plasma. The structure of the magnetic field perturbations and the distribution of the plasma currents that result from inductive interaction are studied. The kinetic effects associated with the finiteness of the absorption and emission currents transporting charge from the body to plasma and back are taken into account. It is found that substantial potentials can be generated on the surface of the body which can sufficiently accelerate particles in the neighborhood. This can be important for understanding the nature of auroral phenomena in the Earth's ionosphere.

A thesis was completed by Dmitri Uzdensky in which magnetic reconnection was examined carefully by a boundary analysis of the reconnection layer. He and Kulsrud did this in the context of constant resistivity magnetohydrody-

namics. They found that the correct theory in this context was definitely that of Sweet and Parker rather than Petschek. However, if one replaces the standard Spitzer resistivity by an anomalous one driven by plasma instabilities on the small scale, then the reconnection can go much faster. Further, the problem with the Petschek theory in the magnetohydrodynamic context was found to be associated with the assumption of constant resistivity. If the resistivity is anomalous then it becomes very space dependent and this seems sufficient to partially reestablish the Petschek mechanism. However, this will not lead to reconnection as fast as the Alfvén speed as is generally assumed. Further, it is crucial to have anomalous resistivity for reconnection to go faster than predicted by Sweet and Parker. Thus, for example, it seems unlikely that reconnection in the interstellar medium, for example, would be very fast unless the reconnection theory is strongly modified away from the standard boundary layer analysis.

2.14 Instrumentation and Software: Sloan Digital Sky Survey

Over the past year, several major milestones were achieved by the SDSS (Sloan Digital Sky Survey). Princeton team members made major contributions in these successes: The Princeton SDSS hardware group (J.E. Gunn and M. Carr), having essentially finished building and commissioning the SDSS camera, have worked primarily on building and finishing other SDSS systems, primarily for the telescope itself, this academic year. The documentation for the camera itself is still being worked on, and a major paper (Gunn, *et al.* 1998) appeared in December describing the camera and its systems.

The 2.5-meter primary mirror of the SDSS telescope was delivered with about 0.6 waves of third-order astigmatism, which appeared when the pressurization hardware, used to prevent print-through of the support structure to the thin faceplate, was removed. It was decided at the time that this could be corrected later, and we designed and built a low-friction air-pressure system to do this. It was installed in January and works as designed; the corrected mirror has no measurable astigmatism, and the device introduced no other problems.

The instrumentation on the telescope was from the beginning controlled by a glycol-water mixture refrigerated by a conventional refrigeration system known to be inadequate while a 'proper' system was designed and built. They received the responsibility for doing this in the early fall, and built a system designed around thermoelectric coolers to do the job. TECs have the enormous advantage over mechanical refrigerators that they work basically differentially from ambient temperature, instead of with essentially fixed operating fluid temperatures. Since we wish to deliver fluid to the instruments at 4C below ambient, this characteristic is ideal. This system was installed in February and works well.

Princeton built the cameras for the SDSS spectrographs but did not originally have responsibility for the liquid nitrogen system which keeps the spectrographic cameras filled. Since the hold time of the small camera dewars is only a few hours, it is necessary to have such a system both to be able to

observe through a night and to avoid having to service the instruments on extremely inconvenient and costly timescales. They were asked to take responsibility for this system in the fall for delivery in the spring when the spectrographs first went on the telescope. The system was delivered in May and was used for the commissioning run and first data run for the first spectrograph. Both systems were constructed at the same time, and the second one is ready for installation on the second spectrograph in mid-August.

The spectrographs need both flat-field and wavelength calibration systems in order to produce scientifically useful data. They were given responsibility for producing the lamps and a new screen for illumination by those lamps in the fall, for delivery this summer. The lamps were finished in June, and were delivered in middle July, along with the screen. The system is currently being installed on the telescope and being interfaced with its control system, which was built by Fermilab and is part of the Programmable Logic Controller (PLC) system used for other telescope control functions.

The Princeton SDSS (Sloan Digital Sky Survey) software group (R. Lupton, Z. Ivezić, M. Strauss, X. Fan, M. Vogeley, D. Schlegel, J. Gunn, G. Knapp, K. Finlator and J. Goldston) have as their primary responsibility the photometric pipeline that automatically reduces the data from the imaging camera on the 2.5 m telescope. Observations with the imaging camera consist of continuous drift scans, with the sky passing through five filters (u' , g' , r' , i' , and z') in turn. The photometric pipeline corrects the data, finds and measures objects, and produces a catalogue of objects.

Following first light from the SDSS camera in May 1998, test data have been taken by drift-scanning the celestial equator. To date, data for about 400 square degrees of sky have been taken in photometric conditions and used to test the performance of the camera, telescope, and photometric software. The output of the photometric pipeline has been used to select objects, for which test spectra were taken with the first of the two SDSS spectrographs (built by a group led by A. Uomoto, JHU). Target selection for galaxies appears to work well, producing a uniform, magnitude limited sample for which well determined redshifts can be determined. Schlegel has incorporated the Schlegel-Finkbeiner-Davis extinction and reddening map into SDSS target selection, and is also working on the selection of standard stars.

The photometric pipeline works reliably and efficiently (most of the time - there are still a few bugs to fix) and has been used to process and reprocess the photometric test data acquired so far. Two major new developments have proved necessary. The first is to detect rapidly moving objects (asteroids) whose positions change significantly on the 7 minute time in which a given point on the sky passes through the SDSS mosaic camera. As well as removing a significant source of contamination for searches for objects of unusual colors, this effort will give a very large catalogue of solar system objects. It is expected that as the absolute astrometry of the data reaches its goal, it should be possible to detect solar system objects out to the Kuiper Belt.

The second development is to take account of the variation of the point spread function (PSF). The PSF varies both across a CCD because of telescope optics and down a CCD

because of seeing variations - this is the bugbear of doing accurate photometry from data taken with short exposures. The problem has been characterized and software to deal with it is now being implemented.

There is interesting science in this seeing variation, of course. The atmospheric contribution to the PSF shows quasi-periodic behavior with typical periods of from a few to over 30 minutes and amplitudes 0.1–0.5 arcsec. The unique design of the SDSS camera reveals, for the first time, that such atmospheric seeing variations are spatially coherent on scales exceeding two degrees. The centroid wander has also been shown to be spatially coherent on these scales in investigations of SDSS astrometry by J. Pier (U.S. Naval Observatory) and colleagues.

Ivezić is also working on source matching code, to match objects found in SDSS with those found in other catalogues - FIRST, IRAS etc. He has produced a set of SDSS images of galaxies across the Hubble sequence, for use in popular textbooks etc. Lupton is helping develop and finish the software which monitors and operates the SDSS telescope and its instruments. Strauss is responsible for independent testing of the spectroscopic pipeline, and for galaxy target selection. He is also working on the selection of quasars and, in collaboration with D. Hogg and D. Eisenstein (IAS), the selection of "bright red galaxies," those which are morphologically similar to those found in the centers of rich clusters.

The Sloan Digital Sky Survey (SDSS) is a joint project of The University of Chicago, Fermilab, the Institute for Advanced Study, the Japan Participation Group, The Johns Hopkins University, the Max-Planck-Institute for Astronomy, Princeton University, the United States Naval Observatory, and the University of Washington. Apache Point Observatory, site of the SDSS, is operated by the Astrophysical Research Consortium. Funding for the project has been provided by the Alfred P. Sloan Foundation, the SDSS member institutions, the National Aeronautics and Space Administration, the National Science Foundation, the U.S. Department of Energy, and the Ministry of Education of Japan.

2.15 Instrumentation and Software: Space Science

M. Reale (electronics engineer) and E. Jenkins have completed their development of a special signal processing system that enables the real-time detection of photoevents in image frames coming from the windowless, electron-bombarded CCD image sensor that flew on the Interstellar Medium Absorption Profile Spectrograph (IMAPS). Laboratory tests of this system demonstrated that faint images are recorded with sharper detail and far less noise than a more conventional recording technique that adds together the digitized raw signals in an accumulating memory. This new system will enable IMAPS to observe much fainter targets than before.

For many years, E. Jenkins has participated as a member of the science team for the Far Ultraviolet Spectroscopic Explorer (FUSE) that was being developed at the Johns Hopkins University. FUSE is a space observatory that can record the difficult 900 – 1200Å wavelength range, one that has not been covered by a major, long-term observatory in orbit since *Copernicus* which flew in the 1970's. FUSE was

launched on June 24, 1999, and this event will ultimately set into motion a research program on interstellar and intergalactic matter to be conducted by E. Jenkins, D. Bowen and T. Tripp, in collaboration with other astronomers on the FUSE science team.

PUBLICATIONS

- Bahcall, N.**, 1998, "Clusters and Superclusters of Galaxies," in *Formation of Structure in the Universe*, eds. A. Dekel and J.P. Ostriker, Cambridge University Press, Cambridge, p. 135.
- Bahcall, N.**, 1998, "Large Scale Structure of the Universe," in *Horizons from Multi-Wavelength Sky Surveys*, Proceedings IAU179 Conference, Baltimore, MD, ed. B.J. McLean, *et al.*, Kluwer Academic Press, p. 317.
- Bahcall, N.**, 1998, "Tracing the Universe with Clusters of Galaxies," in *Large Scale Structure: Tracks and Traces*, 12th Potsdam Cosmology Workshop, eds. V. Muller, *et al.*, World Scientific, p. 137.
- Bahcall, N.**, 1998, "Determining Ω and σ_8 with Clusters of Galaxies," in *Wide Field Surveys in Cosmology*, IAP98, 14th IAP Astrophysics Colloquium, eds. S. Colombi, Y. Mellier and B. Raban, Editions Frontieres, p. 231.
- Bahcall, N.**, 1999, "Determining Cosmological Parameters from Cluster Evolution," in *Evolution of Large Scale Structure*, MPA/ESO Cosmology Conference, eds. A.J. Banday, *et al.* Twin Press, p. 235.
- Bahcall, N.**, & **Fan, X.**, 1998, "The Most Massive Distant Clusters: Determining Ω and σ_8 ," ApJ, 504, 1.
- Bahcall, N.**, & **Fan, X.**, 1998, "A Lightweight Universe?," National Academy of Sciences, 95, 5956.
- Bahcall, N.**, **Ostriker, J.P.**, Perlmutter, S., & Steinhart, P., 1999, "The Cosmic Triangle: Revealing the State of the Universe," Science, 284 1481-1488.
- Baker, J.E., Davis, M., **Strauss, M.A.**, Lahav, O., & Santiago, B.X., 1998, "The Velocity Field Predicted by the Optical Redshift Survey," ApJ, 508, 6-16.
- Blanton, M.**, **Turner, E.L.**, & Wambsganss, J., 1998, "Ultraviolet Images of the Gravitationally Lensed Quadruple Quasar Q2237+0305 with the HST WFPC2," MNRAS, 298, 1223.
- Blitz, L., **Spergel, D.N.**, Teuben, P.J., Hartmann, D., & Butler Burton, W., 1999, "High Velocity Clouds: Building Blocks of the Local Group," ApJ, 514, 818.
- Cen, R.**, 1998, "Supernovae, Pulsars and Gamma-Ray Bursts: A Unified Picture," AJ, 507, L131.
- Cen, R.**, 1998, "Testing Cold Dark Matter Models At Moderate to High Redshift," AJ, 509, 16.
- Cen, R.**, 1999, "An Intrinsic Smoothing Mechanism For Gamma-Ray Burst Spectra in the Fireball Model," AJ, 517, L113.
- Cen, R.**, with Einasto, J., *et al.*, 1999, "Steps toward the power spectrum of matter. I. The mean spectrum of galaxies," AJ, 519, 441.
- Cen, R.**, with Einasto, J., *et al.*, 1999, "Steps toward the power spectrum of matter. II. The biasing correction with σ_8 normalization," AJ, 519, 456.
- Cen, R.**, with Einasto, J., *et al.*, 1999, "Steps toward the power spectrum of matter. III. The primordial spectrum," AJ, 519, 469.
- Cen, R.**, & **Ostriker, J.P.**, 1999, "Where are the Baryons?," AJ, 514, 1.
- Cen, R.**, & **Ostriker, J.P.**, 1999, "Accuracy of Mesh Based Cosmological Hydrocodes: Tests and Corrections," AJ, 517, 31.
- Cen, R.**, & **Ostriker, J.P.**, 1999, "Cosmic Chemical Evolution," AJ, 519, L109.
- Crosas, M., Young, K., **Ivezić, Ž.**, & **Knapp, G.R.**, 1998, "New Atomic Carbon Detections in post-AGB stars," IAU Symposium 191 Poster Session, P4-03, Montpellier, France, Aug 28 - Sept 1, 1998.
- Davé, R.**, Hernquist, L., Katz, N., & Weinberg, D.H., 1998, "Constraining the Metallicity of the Low-Density Ly α Forest Using O VI Absorption," ApJ, 509, 661.
- Davé, R.**, Hernquist, L., Katz, N., & Weinberg, D.H., 1999, "The Low-Redshift Ly α Forest in Cold Dark Matter Cosmologies," ApJ, 511, 521.
- de Mello, D., **Infante, L.**, Menanteau, F., & Vieira, G., 1998, "Faint Interacting Galaxies in Pairs and Group," Boletín de la Academia Nacional de Ciencias, Córdoba, Argentina, 62, 107.
- Diercks, A.H., Deutsch, E.W., Castander, F.J., Corson, C., Gilmore, G., Lamb, D.Q., **Turner, E.L.**, & Wyse, R., 1998, "The Optical Afterglow of GRB971214: R and J Photometry," ApJL, 503, L105.
- Dixon, W.V., Hurwitz, M., Sirk, M.M., & **Jenkins, E.B.**, 1999, "MOES: The Minimal Optic Echelle Spectrometer," in *Ultraviolet-Optical Space Astronomy Beyond HST*, eds. Morse, J.A., Shull, J.M., Kinney, A.L., ASP Conf. Ser., 164, Astronomical Soc. Pacific, San Francisco, 297-300.
- Draine, B.T.**, 1998, "Lensing of Stars by Spherical Gas Clouds," ApJL, 509, L41.
- Draine, B.T.**, 1999, "Diffuse Galactic Emission from Dust Grains," in *3K Cosmology*, eds. L. Maiani, F. Melchiorri, & N. Vittorio AIP Conf. Proceedings 476, AIP, 283.
- Draine, B.T.**, & **Lazarian, A.**, 1998, "Electric Dipole Radiation from Spinning Dust Grains," ApJ, 508, 157.
- Draine, B.T.**, & **Lazarian, A.**, 1999, "Magnetic Dipole Microwave Emission from Dust Grains," ApJ, 512, 740.
- Eikenberry, S.S., Matthews, K.Y., Murphy, T.W., **Nelson, R.W.**, Morgan, E.H., Remillard, R.A., & Munro, M., 1998, "Spectroscopy of Infrared Flares from the Microquasar GRS 1915+105," ApJL, 506, L31-L34.
- Fan, X.**, **Strauss, M.A.**, Annis, J., **Gunn, J.E.**, Hennessy, G.S., **Ivezić, Ž.**, **Knapp, G.R.**, **Lupton, R.H.**, Munn, J.A., Newberg, H.J., Schneider, D.P., & Yanny, B., 1999, "Spectroscopy of Quasar Candidates from SDSS Commissioning Data," in Proceedings of the Maryland October Conference, *After the Dark Ages: When Galaxies Were Young*, eds. Holt, S. & Smith, E., AIP Press, 282.
- Fan, X.**, 1999, "Simulation of Stellar Objects in SDSS Color Space," AJ, 117, 2528-2551.
- Gnedin, N.Y.**, & **Gnedin, O.Y.**, 1998, "Cosmological Neutrino Background Revisited," ApJ, 509, 11.
- Gnedin, O.Y.**, & **Ostriker, J.P.**, 1999, "On the Self-

- consistent Response of Stellar Systems to Gravitational Shocks,” *ApJ*, 513, 626.
- Gnedin, O.Y.**, Hernquist, L., & **Ostriker, J.P.**, 1999, “Tidal Shocking by Extended Mass Distributions,” *ApJ*, 514, 109.
- Gnedin, O.Y.**, Lee, H.M., & **Ostriker, J.P.**, 1999, “Effects of Tidal Shocks on the Evolution of Globular Clusters,” *ApJ*, 522, 935.
- Goodman, J.**, & Dickson, E.S., 1998, “Dynamical Tide in Solar-type Binaries,” *ApJ*, 507, 938.
- Gott, J.R.**, & **Li, L.-X.**, 1998, “Can the Universe Create Itself?,” *Phys. Rev. D*, 58, 023501.
- Gunn, J.E.**, **Carr, M.**, Rockosi, C., Sekiguchi, M., *et al.*, 1998, “The Sloan Digital Sky Survey Photometric Camera,” *AJ*, 116, 3040-81.
- Hayes, W., & **Tremaine, S.**, 1998, “Fitting selected random planetary systems to Titius-Bode laws,” *Icarus*, 135, 549.
- Hilker, **Infante, L.** Vieira, Kissler-Patig, & Richtler, 1999, “The central region of the Fornax cluster. II. Spectroscopy and radial velocities of member and background galaxies,” *A&AS*, 134, 75.
- Hilker, Kissler-Patig, Richtler, **Infante, L.**, & Quintana, 1999, “The central region of the Fornax cluster – I. A catalog and photometric properties of galaxies in selected CCD fields,” *A&AS*, 134, 59.
- Huchra, J.P., **Vogeley, M.S.**, & Geller, M.J., 1999, “The CfA Redshift Survey: Data for the South Galactic Cap,” *ApJS*, 121, 287.
- Infante, L.**, de Mello, D. and Menanteau, F., 1998, “Galaxy Clustering at Small Angular Scales and The Galaxy Merger Rate,” *Boletín de la Academia Nacional de Ciencias, Córdoba, Argentina*, 62, 81.
- Ivezić, Ž.**, & **Knapp, G.R.**, 1998, “Link between Mass-loss and Variability Type for AGB Stars?,” *IAU Symposium 191 Poster Session, P4-03, Montpellier, France, Aug 28 - Sept 1, 1998*.
- Ivezić, Ž.**, Miroshnichenko, A., & Elitzur, M., 1998, “Infrared Emission From Dust Around Be Stars,” *Paris workshop on Be stars*, p. 227, Paris, France, June 9-12, 1997.
- Ivezić, Ž.**, 1998, “IRAS Color-color Diagrams as Indicators of the Stellar Evolutionary Status,” *Hvar Obs. Bull.*, 22, 1, 65.
- Ivezić, Ž.**, 1998, “The Sloan Digital Sky Survey: Astronomical Data for the Next Century,” *Hvar Obs. Bull.*, 22, 1, 117.
- Ivezić, Ž.**, **Knapp, G.R.**, & Elitzur, M., 1998, “Stellar Outflows Driven by Radiation Pressure,” in *Proceedings of The 6th Annual Conference of the Computational Fluid Dynamics Society of Canada*, ed. E. Fournier, IV:13-17.
- Jenkins, E.B.**, & Wallerstein, G., 1999, “Frontiers in absorption line spectroscopy of the interstellar medium of the Galaxy,” in *Ultraviolet-Optical Space Astronomy Beyond HST*, eds. Morse, J.A., Shull, J.M., Kinney, A.L., ASP Conf. Ser., 164, Astronomical Soc. Pacific, San Francisco, 118-130.
- Johnston, K.V., Zhao, H.-S., **Spergel, D.N.**, & Hernquist, L., 1999, “Tidal Streams as Probes of the Galactic Potential,” *ApJ*, 512, L109.
- Junqueira, S., de Mello, D., & **Infante, L.**, 1998, “Morphology Transformation in Pairs of Galaxies,” *A&AS*, 129, 69.
- Kawaguchi, T., Mineshige, S., Umemura, M., & **Turner, E.L.**, 1998, “Optical Variability in Active Galactic Nuclei: Starbursts or Disk Instabilities?,” *AJ*, 504, 671.
- Kepner, J.**, **Fan, X.**, **Bahcall, N.**, **Gunn, J.E.**, & **Lupton, R.**, 1999, “An Automated Cluster Finder: The Adaptive Matched Filter Method,” *ApJ*, 517, 78.
- Kepner, J.**, **Tripp, T.M.**, Abel, T., & **Spergel, D.N.**, 1999, “Absorption-Line Signatures of Gas in Dark Matter Minihalos,” *AJ*, 117, 2063.
- Knapp, G.R.**, Binette, L., Bower, R., Brinks, E., Goudfrooij, P., Hau, G., Pogge, R., & Young, L., 1998, “Panel Discussion: Star Formation in Early-Type Galaxies,” *Star Formation in Early-Type Galaxies*, eds. Cepa, J. & Carral, P., A.S.P. Conference Proceedings, 163, 142-149.
- Knapp, G.R.**, Young, K., & Crosas, M., 1999, “The Circumstellar Envelope of Π^1 Gru,” *A&A*, 346, 175-80.
- Knapp, G.R.**, 1999, “Cold Gas and Star Formation in Elliptical Galaxies,” in *Star Formation in Early-Type Galaxies*, eds. Cepa, J. & Carral, P., A.S.P. Conference Proceedings, 163, 119-134.
- Lazarian, A.**, & **Draine, B.T.**, 1999, “Thermal Flipping and Thermal Trapping – New Elements in Grain Dynamics,” *ApJ*, 516, L37.
- Li, L.-X.**, 1999, “Time Machines Constructed from Anti-de Sitter Space,” *Phys. Rev. D*, 59, 084016.
- Li, L.-X.**, & **Paczynski, B.**, 1998, “Transient Events from Neutron Star Mergers,” *ApJ*, 507, L59.
- Li, L.-X.**, & **Gott, J.R.**, 1998, “Inflation in Kaluza-Klein Theory: Relation between the Fine-Structure Constant and the Cosmological Constant,” *Phys. Rev. D*, 58, 103513.
- Ma, C., Caldwell, R., **Bode, P.**, & Wang, L., 1999, “The Mass Power Spectrum in Quintessence Cosmological Models,” *ApJ*, 521, L1.
- Miroshnichenko, A., **Ivezić, Ž.**, Vinković, D., & Elitzur, M., 1999, “On Protostellar Disks in Herbig Ae/Be Stars,” *ApJ*, 520, L115.
- Nelson, R.W.**, & **Tremaine, S.**, 1998, “Linear Response, Dynamical Friction, and the Fluctuation-Dissipation Theorem in Stellar Dynamics,” *MNRAS*, 306, 1-21.
- Oh, S.P.**, **Spergel, D.N.**, & Hinshaw, G., 1999, “An Efficient Technique to Determine the Power Spectrum from Cosmic Microwave Background Sky Maps,” *ApJ*, 510, 551.
- Park, M.-G.**, & **Ostriker, J.P.**, 1998, “Hydrodynamics of Accretion onto Black Holes,” *Adv. Sp. Rev.*, 22, 7, 951-960.
- Richstone, D., Ajhar, E.A., Bender, R., Bower, G., Dressler, A., Faber, S.M., Filippenko, A.V., Gebhardt, K., Green, R., Ho, L.C., Kormendy, J., Lauer, T.R., Magorrian, J., & **Tremaine, S.**, 1998, “Supermassive black holes and the evolution of galaxies,” *Nature*, 395, A14.
- Sellwood, J., **Nelson, R.W.**, & **Tremaine, S.**, 1998, “Resonant Thickening of Disks by Satellite Galaxies,” *ApJ*, 506, 590-599.
- Sellwood, J.A., & **Goodman, J.**, eds., 1999, “Astrophysical Discs,” ASP Conf. Ser. 180.

- Spergel, D.N.**, 1998, “Do We Live in a Low-density Universe?,” *Class. Quantum Grav.*, 15, 1.
- Strauss, M.A.**, 1998, “Large-Scale Structure in the Distribution of Galaxies as a Probe of Cosmological Models,” *Nature*, 395, A9–A13, (*Invited review in a supplement entitled, “Optical astronomy: A view to the future”*).
- Strauss, M.A.**, 1999, “Redshift Surveys of the Local Universe,” in *Formation of Structure in the Universe*, ed. A. Dekel & J.P. Ostriker, Cambridge University Press, 172–212.
- Suginohara, M., Suginothara, T., & Spergel, D.N.**, 1999, “Detecting $z > 10$ objects through carbon, nitrogen and oxygen emission lines,” *ApJ*, 512, 547.
- Tremaine, S.**, 1998, “Resonance relaxation in protoplanetary disks,” *AJ*, 116, 2015.
- Tremaine, S., & Ostriker, J.P.**, 1999, “Relaxation in stellar systems, and the shape and rotation of the inner dark halo,” *MNRAS*, 306, 662.
- Tripp, T.M., Lu, L., & Savage, B.D.**, 1998, “The Relationship Between Galaxies and Low Redshift Weak Ly α Absorbers in the Directions of H1821+643 and PG 1116+215,” *ApJ*, 508, 200.
- Uzdensky, D., & **Kulsrud, R.**, 1998, “Viscous Boundary Layer near the Center of the Resistive Reconnection Region,” *Physics of Plasmas*, 5, 3249.
- Vicini, B., Natta, A., Marconi, A., Testi, L., Hollenbach, D., & **Draine, B.T.**, 1999, “A Near-Infrared Study of the Planetary Nebula NGC 2346,” *A&A*, 342, 823.
- Wallerstein, G., & **Knapp, G.R.**, 1998, “Carbon Stars,” *ARA&A*, 36, 369–433.
- Wang, Y., Spergel, D.N., & Strauss, M.A.**, 1999, “Cosmology in the Next Millennium: Combining Microwave Anisotropy Probe and Sloan Sky Survey Data to Constrain Inflationary Models,” *ApJ*, 510, 20.
- Wang, Y., Spergel, D.N., & Strauss, M.A.**, 1999, “Model-Independent Measurement of the Primordial Power Spectrum,” in proceedings of *Particle Physics and the Early Universe (COSMO-98)*, ed D.O. Caldwell, AIP.
- Wang, Y., Bahcall, N., & Turner, E.L.**, 1998, “A Catalog of Color-Based Redshift Estimates for $z < 4$ Galaxies in the Hubble Deep Field,” *AJ*, 116, 2081.
- Weingartner, J.C., & Draine, B.T.**, 1999, “Interstellar Depletion onto Very Small Dust Grains,” *ApJ*, 517, 292.
- Willick, J.A., & **Strauss, M.A.**, 1998, “Maximum-Likelihood Comparison of Tully-Fisher and Redshift Data. II. Results from an Expanded Sample,” *ApJ*, 507, 64–83.
- Wiegert, P., & **Tremaine, S.**, 1999, “The evolution of long-period comets,” *Icarus*, 137, 84.
- Yonehara, A., Mineshige, S., Manmoto, T., Fukue, J., Umemura, M., & **Turner, E.L.**, 1998, “An X-ray Microlensing Test of AU-Scale Accretion Disk Structure in Q2237+0305,” *ApJ*, 501, L41.
- Yonehara, A., Mineshige, S., Fukue, J., Umemura, M., & **Turner, E.L.**, 1999, “Microlens Diagnostics of Accretion Disks in Active Galactic Nuclei,” *A&A*, 343, 41.

David N. Spergel, Professor and Associate Chair

