Annual Report  
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1. PERSONNEL

During the reporting year the research staff consisted of Neta Bahcall, Renyue Cen, Bruce Draine, Edward Fitzpatrick, 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 Greg Bryan, Alex Lazarian, Željko Ivezic, Todd Tripp, Michael Vogeley, and Yun Wang. Christophe Alard (Cambridge) and Janusz Kaluzny (Warsaw University Observatory) held visiting research appointments during summer and fall 1997. Edward Fitzpatrick left in summer 1997 to take up a faculty position at Villanova University, and Michael Richmond left in summer 1997 to begin a faculty position at the Rochester Institute of Technology. Tatsushi Suginohara returned to the University of Tokyo in March 1998. Turner was on research leave during the fall term, and Goodman and Paczyński were on leave during the spring.

Neta Bahcall was inducted into the National Academy of Sciences. J. Richard Gott received Princeton’s President’s Award for Distinguished Teaching, as well as the highest award of the Astronomical League, the national association of amateur astronomers. Scott Tremaine received the Dannie Heinemann Prize for Astrophysics from the American Astronomical Society and the Dirk Brouwer Award from the Division of Dynamical Astronomy of the AAS. Two special celebrations were held: the department hosted a successful festschrift celebrating Russell Kulsrud’s 70th birthday, and the Lyman Spitzer Building was dedicated at the Princeton Plasma Physics Laboratory.

The 1998 Lyman Spitzer, Jr. Lecture Series was given by Reinhard Genzel on “Galaxies and galactic nuclei in the infrared”.

2. RESEARCH PROGRAM
2.1. Cosmological models

N. Bahcall and X. Fan (graduate student) summarized the constraints on the mass density of the universe as determined from several independent observational methods. The methods include the observed masses and mass-to-light ratios of galaxies, groups and clusters as a function of scale; the observed baryon fraction in clusters; and the evolution of cluster abundance. Their summary, “A Lightweight Universe?” was published as an Inaugural Article in the Proceedings of the National Academy of Sciences. They showed that these independent methods all indicate that the mass density of the universe is sub-critical, insufficient to halt the universal expansion, and reveal a consistent picture of a lightweight universe with only \( \sim 20–30\% \) of the critical density. Thus, the universe is likely to expand forever.

D. Spergel, N. Cornish (Cambridge), and G. Starkman (Case Western) are exploring the possibility that the universe has non-trivial topology. Observations of fluctuations in the microwave cosmic background radiation (CBR) can yield information not only about the geometry of the universe, but also about its topology. If the universe has negative curvature, then the characteristic scale for the topology of the universe is the curvature radius. Thus, if we are seeing the effects of the geometry of the universe, we can hope to soon see signatures of its topology. The cleanest signature is written on the microwave sky: there should be thousands of pairs of matched circles. These circles could be used to determine the precise topology and volume of the universe.

W. Colley (graduate student) has measured the topology of the large-scale structure observed in the Las Campanas Redshift Survey (LCRS). This survey provides deep slices showing galaxies out to a redshift \( z \approx 0.2 \), giving us our best current picture of the structure of the universe on the largest scales. One can see many voids and walls. Colley filtered these data with a smoothing length of \( 20h^{-1}\text{Mpc} \) \( (h = H_0/100\text{km s}^{-1}\text{Mpc}^{-1}, \text{where } H_0 \text{ is the Hubble constant}) \) so as to recover fluctuations that are still in the linear regime. Thus, if the original fluctuations were Gaussian random-phase, so should be the topology of the smoothed maps. He compared the topology as measured by the genus, the number of high-density spots minus the number of low-density spots, as a function of density threshold. The results are in extraordinarily good agreement with the theoretical random-phase curve, showing that this pattern of galaxy clustering could have grown by gravitational instability from random quantum fluctuations in a standard inflationary Big-Bang model.

J. R. Gott and L.-X. Li (graduate student) have written two papers considering quantum effects in spacetimes with multiply connected topologies and closed timelike curves. A previous calculation of the renormalized energy-momentum tensor in Misner space showed a blowup as the Cauchy horizon is approached, which was the basis for Hawking’s Chronology Protection Conjecture forbidding time travel. However, this model has a non-self-consistent
vacuum—an adapted Minkowski vacuum, which does not solve Einstein’s field equations for the Misner geometry. In their first paper, Li and Gott showed that if, instead, an adapted Rindler vacuum is used one can obtain a self-consistent vacuum where the renormalized energy-momentum tensor is well behaved as the Cauchy horizon is approached and self-consistently solves Einstein’s field equations for Misner space. The second paper explores whether the laws of physics permit the universe to be its own mother. An inflationary universe can create baby universes. If one of those baby universes turns out to be the inflationary universe that one started with, then there is an early region of closed timelike curves in the model. In such a case the universe has no earliest event. Gott and Li show how there are self-consistent vacuum states, and how an arrow of time with pure retarded potentials naturally arises in such models.

M-G. Park and Gott have shown how a study of gravitational lens separations as a function of quasar redshift can yield data on the curvature of the universe. The observed separations become smaller with increasing source redshift, and Park and Gott show that the observations are not compatible with the “standard” gravitational lensing statistics model in a flat universe. They also tried various open and flat cosmologies, galaxy mass profiles, galaxy merging and evolution models, and lensing aided by clusters to explain the correlation, but the data are not compatible with any of these possibilities within the 95% confidence limit.

2.2. Cosmic background radiation

D. Spergel is a member of the science team for the Microwave Anisotropy Probe (MAP) satellite (http://map.gsfc.nasa.gov). Fluctuations in the CBR trace the density fluctuations 300,000 years after the Big Bang. The COBE satellite has already established that these fluctuations are present at a level consistent with the gravitational growth of structure from small primordial fluctuations. MAP will survey the CBR temperature and polarization at 5 frequencies ranging from 22–90 GHz, at angular resolution as high as 0.21°. These high-resolution maps should determine whether the primordial fluctuations are adiabatic density variations (as predicted by inflation) or isocurvature fluctuations (as predicted in alternative models of structure formation). If the fluctuations are adiabatic, MAP should yield precision measurements of the geometry of the universe, the ratio of the density in baryons to the density in non-baryonic dark matter, the ratio of dark matter density to radiation density, as well as the primordial spectrum of fluctuations. If the fluctuations are not adiabatic, then we will have to rethink our standard ideas about the origin of structure.

S. P. Oh (graduate student), Spergel and G. Hinshaw (Goddard) developed an efficient
technique to determine the power spectrum from CBR sky maps. Existing algorithms for computing the angular power spectrum of a pixelized map typically require O($N^3$) operations and O($N^2$) storage, where $N$ is the number of independent pixels. The MAP and Planck satellites will produce megapixel maps of the CBR temperature at multiple frequencies; thus existing algorithms are not computationally feasible. The new algorithm requires only O($N^2$) operations and O($N^{1.5}$) storage, representing a million-fold speedup in determining the power spectrum from MAP or Planck.

A. Refregier, Spergel and T. Herbig (Physics) analyzed the extragalactic foregrounds for the MAP mission. While the major contributor to CBR anisotropies is the sought-after primordial fluctuations produced at the surface of last scattering, other effects can also be important. They show that the dominant “noise” sources are the Sunyaev-Zel’dovich effect from rich clusters and gravitational lensing. MAP should detect about 50 discrete sources and 10 clusters directly. Fainter clusters can be probed by cross-correlating MAP with cluster positions extracted from existing catalogs. Finally, they consider probing the hot gas on supercluster scales by cross-correlating the CBR with galaxy catalogs. Assuming that galaxies trace the gas, they show that a cross-correlation between MAP and the APM galaxy catalog should yield a marginal detection, or at least a four-fold improvement on the COBE upper limits for the rms Compton y-parameter.

Y. Wang, Spergel and E. Turner have investigated the implications of anisotropies in the CBR for possible large-scale variations in Hubble’s constant. Low-amplitude (linear regime) cosmic density fluctuations lead to variations in the locally measurable value of $H_0$ (denoted as $H_L$). For three currently viable structure formation models based on cold dark matter (CDM)—tilted CDM, ΛCDM, and open CDM—normalized by the 4-year COBE DMR data, the fractional variations in $H_L$ are of order 3–6% (95% confidence interval) in a sphere 200$h^{-1}$ Mpc in diameter, and of order 1–2% if the size of this sphere is doubled. The measured CBR dipole (caused by the Galaxy’s peculiar velocity with respect to the CBR rest frame) provides additional constraints on $\Delta H$ that supplement our limited knowledge of the power spectrum. In the limiting case where the power spectrum is unknown, the observed CBR dipole alone provides a very robust limit, $\langle \delta^2_{H_0} \rangle^{1/2} < 10.5 \, h^{-1} \, \text{Mpc}/R$ in a sphere of radius $R$ (95% confidence level). Thus, variations between currently available local measures of $H_0$ and its true global value of a few to several percent are to be expected and differences as large as 10% are possible.
2.3. Large-scale structure

J. Ostriker summarized the development of large-scale cosmic structure at the 1998 San Diego meeting of the American Astronomical Society. There is now a standard model for the growth of structure in the universe which is clearly correct in general form, although the details remain uncertain. Quantum fluctuations in the early universe, amplified by inflation, are probably the original source of perturbations in an otherwise uniform universe. The amplitude of these perturbations is determined by observed CBR fluctuations and the shape is predicted by standard theory, so long as some form of CDM constitutes most of the mass density. Putting these initial conditions, with standard atomic physics and the equations of hydrodynamics, into a sufficiently detailed computational model, allows one to predict where and when galaxies will form. Very large scale simulations completed to date of models such as the concordance (Ostriker and Steinhardt) model indicate quite good agreement with a suite of observational constraints from Ly$\alpha$ clouds at redshift 3 to clusters of galaxies at redshift zero. Open models with $\Omega_m < 1$ seem best at reproducing all of these properties, as well as the large-scale distribution of galaxies and intergalactic gas. A particularly interesting and robust conclusion is reached concerning the distribution of baryons. For a wide range of viable cosmological models, the fraction of baryons that condenses to stars and cold gas (in galaxies) is $20 \pm 10\%$. Of the remaining baryons in the intergalactic medium, the fractions in the hot ($T > 10^7 K$), intermediate ($10^7 K > T > 10^5 K$) and warm ($10^5 K > T$) components are $20 \pm 7\%$, $55 \pm 10\%$, and $15 \pm 5\%$ respectively. Thus the majority of cosmic baryons are found in intermediate-temperature regions ($T \sim 10^6 K$), where they should be discovered by soft X-ray observations.

R. Cen has examined all currently viable CDM models in great detail to find ways to differentiate between them. The COBE measurements of CBR fluctuations and the local abundance of rich clusters of galaxies provide the two most powerful constraints on cosmological models. When all variants of the standard CDM (SCDM) model are subjected to the combined constraints, the power spectrum of any model is fixed to $\sim 10\%$ accuracy in both 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 the differences growing dramatically with redshift. The observational constraints include the correlation function of rich clusters of galaxies, the galaxy power spectrum, the evolution of cluster abundance, gravitational lensing by moderate-to-high redshift clusters, the Ly$\alpha$ forest, damped Ly$\alpha$ systems, high-redshift galaxies, reionization of the universe and future CBR experiments. The combined power of several or all of these observations is tremendous. Thus, we 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.
Ostriker, M. Blanton (graduate student), Cen and M. Strauss used large-scale hydrodynamic simulations (with heuristic criteria for galaxy formation) to investigate the bias factor \( b(R) = \frac{\sigma_g(R)}{\sigma(R)} \), where \( \sigma_g(R) \) is the variance of galaxy counts in spheres of radius \( R \) and \( \sigma(R) \) is the same for mass. They found that the bias factor varies from 2.6 at \( 1 \, h^{-1} \text{Mpc} \) to 1.2 at \( 30h^{-1} \text{Mpc} \). 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 also found that the relationship between the galaxy and mass density fields is a function of galaxy age. On large scales, older galaxies are highly biased \( (b \sim 1.7) \) and strongly correlated \( (r \sim 1.0) \) with the mass density field; younger galaxies are not biased \( (b \sim 0.8) \) and only weakly correlated \( (r \sim 0.5) \) with the mass. Thus linear bias is inadequate to describe the relationship between galaxies and mass.

Wang, Spergel and Strauss have explored combining data from MAP with data from the upcoming Sloan Digital Sky Survey (SDSS) to constrain inflationary models. The existence of primordial adiabatic Gaussian random-phase density fluctuations is a generic prediction of inflation. The properties of these fluctuations are completely specified by their power spectrum. The basic cosmological parameters and the primordial power spectrum together completely specify predictions for the CBR fluctuations and large-scale structure. If we assume that the cosmological parameters are known a priori, the combined data from MAP and SDSS can constrain the primordial power spectrum to \( \sim 10\% \) accuracy for \( k \sim 0.01h \, \text{Mpc}^{-1} \), and to \( \sim 1\% \) accuracy for \( k \sim 0.1h \, \text{Mpc}^{-1} \). The uncertainty in the primordial power spectrum increases by less than a factor of 2 if we solve simultaneously for the cosmological parameters \( h, \Lambda, \Omega_b, \tau_{ri} \), and the effective bias \( b_{\text{eff}} \) between the matter density field and the galaxy redshift density field.

L. A. Phillips (graduate student) and Turner have analyzed bright-end \( (K = 10–17) \) galaxy counts from a number of near-infrared galaxy surveys. All these surveys agree that the observed near-infrared galaxy number counts are inconsistent with a simple no-evolution model. They examined evolutionary effects and a local underdensity as possible causes of this effect and found that the data are fit by either a factor of 1.7–2.4 deficiency of galaxies out to redshift \( z = 0.10–0.23 \), or by unexpectedly strong low-redshift evolution in the K-band, leading to corrections at \( z = 0.5 \) that are as much as 60% larger than accepted values. The former possibility would imply that the local expansion rate on scales of several hundred Mpc exceeds the global value of \( H_0 \) by up to 30% and that the amplitude of very large-scale density fluctuations is far larger than expected in any current cosmogonic scenario. The latter possibility would mean that even the apparently most secure aspects of our understanding
of galaxy evolution and spectral energy distributions are seriously flawed.

Wang, Bahcall and Turner derived empirical color-redshift relations for galaxies in the Hubble Deep Field (HDF). The dispersion between the estimated redshifts and the spectroscopically observed ones is small, ranging from $\sigma_z \simeq 0.03$ to 0.1 for $z < 2$ galaxies, and from $\sigma_z \simeq 0.14$ to 0.36 for $2 < z < 4$. They applied the color-redshift relations to the HDF photometric catalog and obtained estimated redshifts that are consistent with those derived from spectral template fitting methods. The advantages of the color-redshift relations are that they are simple to use and do not depend on the assumption of particular spectral templates; they provide model-independent redshift estimates for $z < 4$ galaxies using only multi-band photometry. They have used these results to investigate the redshift distribution of galaxies in the HDF and found peaks that suggest large-scale clustering of galaxies to at least $z \sim 1$, consistent with those identified in spectroscopic probes of the HDF.

Strauss carried out a variety of observational and theoretical analyses of large-scale structure. In collaboration with L. Guzzo (Milan), K. Fisher (Texas), R. Giovanelli and M. Haynes (Cornell), he analyzed the clustering statistics and small-scale velocity dispersion of subsamples of galaxies selected by morphology from the Pisces-Perseus redshift survey. They showed that the small-scale velocity dispersion is a strong function of morphological type. With R. Kim (graduate student), he developed a new method for measuring skewness and kurtosis from redshift surveys, which is appreciably more robust than the standard moments technique used in the literature. With Ostriker and Cen, he developed a new measure of the small-scale velocity dispersion, making it explicitly a function of local density. They showed directly what had been suspected for years: that the velocity field in the field (i.e., outside of clusters) is very quiet. This is a powerful new statistic to distinguish cosmological models. With D. Goldberg (graduate student), he carried out an analysis of the effect of baryon density on the average-scale power spectrum of density, and showed that (with luck) it should be a measurable effect on the SDSS power spectrum. With Y. Sigad, A. Eldar, A. Dekel (Hebrew University) and A. Yahil (Stony Brook), he made a detailed comparison of the observed density distribution of IRAS galaxies with that inferred from peculiar velocities. The comparison is consistent with gravitational instability theory, allowing a constraint on the quantity $\beta \equiv \Omega^{0.6}/b = 0.89 \pm 0.12$.

Vogeley showed that statistical analysis of the unresolved light in the Hubble Deep Field (HDF) strongly constrains possible sources of the optical Extragalactic Background Light (EBL). 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. To test for the statistical signature of previously undetected sources, he estimated the auto-, cross-,
and color correlations of the “sky” in the HDF that remains after masking objects brighter than $I_{814} = 30$ mag. Auto- and cross-correlations of surface brightness in the $V_{606}$ and $I_{814}$ bandpasses are well-fitted by $\omega(\theta) \sim 10^{-6}(\theta/1'')^{-0.6}$ up to 10''. This measurement yields the most stringent limits to date on small-scale structure in the night sky.

An important implication of Vogeley’s work is that, unless there is a truly uniform optical background, the mean EBL is likely to be within a small fraction of the surface brightness from detected galaxies. No currently plausible sources of additional EBL satisfy the constraints that they (1) would not have already been detected, (2) contribute EBL comparable to that from detected galaxies, and (3) do not produce EBL fluctuations in excess of the upper limits set by correlations in the HDF. These constraints admit only a confusion-limited population of extremely low surface-brightness objects that is disjoint from the parameter space of all detected galaxies. Extrapolation of detected galaxy counts to zero flux would add only a few percent to the EBL. Diffuse intergalactic light clustered similarly to faint galaxies could explain some of the observed correlations but would contribute at most a few $\times 10\%$ to the mean EBL.

Vogeley initiated a project with J. Gunn to further constrain fluctuations in the EBL by combining analysis of deep Hubble Space Telescope (HST) WFPC2 imaging with ground-based imaging to be taken in drift-scan mode with the Apache Point Observatory 3.5-meter telescope. This analysis will be applied to the HDF and other deep HST images, including the HDF South.

Vogeley reviewed measurements of the power spectrum of density fluctuations from galaxy redshift surveys and discussed advances that will be possible with the SDSS. This review emphasized the difficulties of high-precision power spectrum estimation in the presence of Galactic extinction, photometric errors, galaxy evolution, clustering evolution, and uncertainty about the background cosmology. Discussed in this review are some of the ways in which the SDSS seeks to overcome these obstacles.

Strauss and Vogeley, with M. Tegmark (IAS), A. Hamilton (Colorado), and A. Szalay (Johns Hopkins) showed how precision measurements of the galaxy power spectrum $P(k)$ require a data analysis pipeline that is both fast enough to be computationally feasible and accurate enough to take full advantage of high-quality data. To improve speed, Karhunen-Loève power-spectrum estimation can be accelerated with a quadratic data compression scheme. To improve accuracy, they derived analytic expressions for handling the integral constraint, since it is crucial that finite volume effects are accurately corrected for on scales comparable to the depth of the survey. Also shown is that for data analysis methods based on counts in cells, such as the Karhunen-Loève and quadratic techniques, multiple constraints can be included via simple matrix operations, thereby rendering the results less sensitive to
galactic extinction and mis-estimates of the radial selection function. They describe a data analysis pipeline that does justice to the increases in both quality and quantity of data that upcoming redshift surveys will provide. It involves using three analysis techniques in conjunction: a traditional Fourier approach on small scales, a pixelized quadratic matrix method on large scales and a pixelized Karhunen-Loève eigenmode analysis to probe anisotropic effects such as redshift space distortions, residual extinction, and radial and selection function errors.

Vogeley and A. Connolly (Johns Hopkins) analyzed the effect of uncertainty in corrections for Galactic extinction and zero-point extinction and photometry errors on estimates of the three-dimensional power spectrum from the SDSS and other deep surveys. 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. For the SDSS, errors in the extinction map used to correct apparent galaxy magnitudes can be the dominant source of systematic error on wavelength scales of \( \lambda > 300h^{-1}\) Mpc, just where it is hoped that the SDSS will provide a crucial link between our current knowledge of fluctuations in the present-epoch galaxy distribution and the mass distribution at redshift \( z = 10^3 \) probed by CBR anisotropy experiments. 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.

Cen, in collaboration with J. Einasto (Estonia), M. Einasto (Estonia), E. Tago (Estonia), A. A. Starobinsky (Moscow), F. Atrio-Barandela (Spain), V. Müller (Potsdam), A. Knebe (Potsdam), P. Frisch (Göttingen), H. Andernach (Mexico) and D. Tucker (Fermilab), has analyzed the power spectrum of galaxies using published data. On intermediate and small scales the power spectrum is best given by the two-dimensional distribution of APM galaxies. 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 three-dimensional data, which are reduced in amplitude to the power spectrum of APM galaxies. They find that the available data indicate the presence of two different populations in the local universe. Samples of clusters of galaxies as well as the APM 3-D, IRAS QDOT, and SSRS+CfA2 galaxy surveys cover relatively large regions in the universe where rich, medium and poor superclusters are well represented. The mean power spectrum of these samples has a relatively sharp maximum at wavenumber \( k = 0.05 \pm 0.01h\) Mpc\(^{-1}\), followed by a power-law spectrum of index \( \approx -1.9 \) toward smaller scales. The power spectrum found from LCRS data represents regions of the universe with medium-rich and poor superclusters; it is flatter around the maximum. They argue that the former power spectrum probably corresponds to a fair sample of the universe.
Cen, in collaboration with J. Einasto (Estonia), M. Einasto (Estonia), E. Tago (Estonia), V. Müller (Potsdam), A. Knebe (Potsdam), F. Atrio-Barandela (Spain) and D. Tucker (Fermilab), suggests a new method to find $\sigma_8$, the rms mass fluctuation in a sphere of radius $8h^{-1}$ Mpc. The method is based on an integration of the mean power spectrum of galaxies, which is then reduced to a power spectrum of the mass using a simple relation based on the fraction of mass in galaxies, which is determined from detailed modeling of void evacuation for various cosmological models. They find $\sigma_8 = 0.89 \pm 0.05$ for galaxies, and $\sigma_8 = 0.68 \pm 0.06$ for mass.

### 2.4. Intergalactic medium and galaxy formation

G. Bryan, in collaboration with M. Machacek (Northeastern), P. Anninos and M. Norman (NCSA), used Eulerian hydrodynamic simulations to study the properties of the Ly$\alpha$ forest at redshifts $z \simeq 2–5$. As a first step towards using these simulations to constrain cosmological parameters, they performed a numerical resolution study to examine the robustness of the predicted quantities. They found that the column density distribution is relatively insensitive to spatial resolution, but that the distribution of the Doppler b-parameter, which is a measure of linewidth, depends sensitively on resolution, decreasing as the resolution increases. This is important because the new predicted distribution for the SCDM model is now significantly lower than observed. The same group, along with A. Meiksin (Edinburgh), has begun the second step of this project, to use simulations of a number of cosmological models to constrain their parameters. In particular, they have found that the shape of the column density distribution is a sensitive probe of the amplitude of fluctuations on the $\sim 0.5$ Mpc scale at $z \sim 3$. The observed shape appears to favor models with more small-scale power (such as models including massive neutrinos or a tilted initial spectrum), over those that have less power on small scales. They have also found that the distribution of b-parameters is sensitive to the power spectrum.

J. Kepner (graduate student), Bryan, and Spergel have examined the formation of galaxy-sized objects in hydrodynamic simulations, using a new adaptive-mesh method that combines the shock-capturing ability of Eulerian hydrodynamics codes with adaptive mesh placement for high resolution in regions of large density. They examined the formation and evolution of cold-gas disks (star formation was not included) and found that, as previously predicted, they formed inside-out by accreting high-angular momentum material at late times. Two cosmological models were used, SCDM and ΛCDM, and the disk sizes and specific angular momenta for both were similar to those observed.

Bryan collaborated with T. Abel and Norman to explore the formation of the first
non-linear baryonic objects in models of hierarchical structure formation. These objects, with masses around \(10^6 \, M_\odot\), form at \(z \sim 20\) in most models. They used an adaptive-mesh hydrodynamics code, and a nine-species non-equilibrium chemistry model which included hydrogen, helium and the species relevant for the formation of molecular hydrogen. The clouds were initially Jeans stable, but collapse occurred when the molecular hydrogen fraction (which is the primary coolant since the gas composition is primordial) reached \(\sim 10^{-3}\). There is evidence for fragmentation on the scale of a few hundred solar masses. Densities as high as \(10^5 \, \text{cm}^{-3}\) and proper length scales as small as 0.02 pc (a spatial dynamic range of \(10^5\)) were resolved.

Cen and R. Simcoe (undergraduate student) have analyzed the sizes, shapes and correlations of Ly\(\alpha\) clouds produced by a hydrodynamic simulation of a spatially flat CDM universe with a non-zero cosmological constant (\(\Omega_0 = 0.4, \Lambda_0 = 0.6, \sigma_8 = 0.79\)), over the redshift range \(2 \leq z \leq 4\). The Ly\(\alpha\) clouds range in size from several kpc to about a hundred kpc, and in shape from round, high column-density regions with \(N_{\text{HI}} \geq 10^{15} \, \text{cm}^{-2}\) to low column-density sheet-like structures with \(N_{\text{HI}} \leq 10^{13} \, \text{cm}^{-2}\). The most common shape resembles a flattened cigar. The physical size of a typical cloud grows with time roughly as \((1 + z)^{-3/2}\) while its shape hardly evolves. These results demonstrate that any simple model with a population of spheres (or other shapes) of a uniform size is oversimplified; they also illustrate why the use of double quasar sightlines to set lower limits on cloud sizes is useful only when the perpendicular sightline separation is small (\(\Delta r \leq 50h^{-1}\) kpc). Finally, they conjecture that high column-density Ly\(\alpha\) clouds (\(N_{\text{HI}} \geq 10^{15} \, \text{cm}^{-2}\)) may be the progenitors of the lower redshift faint blue galaxies, since their correlation length, number density (extrapolated to lower redshift) and masses are in fair agreement with those observed.

Cen, in collaboration with M. Rauch (Caltech), J. Miralda-Escudé (Penn), W.L.W. Sargent (Caltech), T. A. Barlow (Caltech), D. Weinberg (Ohio State), L. Hernquist (Santa Cruz), N. Katz (Massachusetts) and Ostriker, has measured the distribution of the flux decrement caused by Ly\(\alpha\) forest absorption from intervening gas in the lines of sight to high-redshift quasars from a sample of seven high-resolution quasar spectra obtained with the Keck Telescope. The observed flux decrement distribution function (FDDF) is compared to the FDDF from two simulations of the Ly\(\alpha\) forest: a CDM model with \(\Omega = 0.4, \Lambda = 0.6\) (LCDM), computed with the Eulerian code of Cen and Ostriker, and a standard CDM model with \(\Omega = 1\) (SCDM) computed with the SPH code of Hernquist, Katz, and Weinberg. Good agreement is obtained between the shapes of the simulated and observed FDDFs for both simulations after fitting only one free parameter, which controls the mean flux decrement. The difference between the predicted FDDFs from the two simulations is small, and arises mostly from a different temperature in the low-density gas (caused by different assumptions about the reionization history in the two simulations), rather than differences between the
two cosmological models per se, or numerical effects in the two quite different codes. A measurement of the parameter $\mu \propto \Omega_b^2 h^3/\Gamma$ (where $\Gamma$ is the HI ionization rate due to the ionizing background) is obtained by requiring the mean flux decrement in the simulations to agree with observations. Using a lower limit $\Gamma > 7 \times 10^{-13} \text{ s}^{-1}$ from the abundance of known QSOs, they derive a lower limit on the baryonic matter density, $\Omega_b h^2 > 0.021 \pm 0.017$ for the $\Lambda$CDM (SCDM) model. The measurement of $\mu(z)$ allows a determination of the evolution of the ionizing radiation field with redshift; the models predict an intensity that is approximately constant with redshift, which is in agreement with the assumption that the ionizing background is produced by known quasars for $z < 3$, but requires additional sources of ionizing photons at higher redshift given the observed rapid decline of the quasar abundance.

Cen, with S. Phelps (graduate student), Miralda-Escudé and Ostriker, has examined the correlation function of Ly$\alpha$ clouds along the line of sight in a $\Lambda$CDM cosmological model. A consistent picture seems to emerge: the correlation strength for a given set of objects is positively correlated with their characteristic global density, and the differences among the correlations of galaxies, Ly$\alpha$ clouds and mass reflect the differences in density that each trace. They find that the galaxies are biased over mass by a factor of $\sim 3.0$, in accord with recent observations of high-redshift galaxies. The correlation strength of Ly$\alpha$ clouds with column densities of $10^{13}$–$10^{14} \text{ cm}^{-2}$ is comparable to that of the total mass.

Cen and Ostriker use high-resolution cosmological simulations of a $\Lambda$CDM model 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 presently having a temperature in the range $10^{5}$–$7\text{K}$. Thus, not only is the universe dominated by dark matter, but more than 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 inter-cluster gas along the line of sight, absorption lines in X-ray and UV quasar spectra [e.g., O VI (1032,1038)A lines, OVII 574eV line] strong emission lines (e.g., O VIII 653 eV line), and low-redshift, broad, low column-density Ly$\alpha$ absorption lines.

Tripp completed a study with L. Lu (Caltech) and B. Savage (Wisconsin) of the relationship between low-redshift Ly$\alpha$ clouds and galaxies based on HST spectroscopy of two QSOs, H1821+643 and PG1116+215. The high signal-to-noise of the HST spectra of these QSOs enables the detection of very weak Ly$\alpha$ absorption lines: 26 Ly$\alpha$ lines with rest equivalent width $W_r > 50 \text{ m}\AA$ are detected toward H1821+643 and 13 are detected toward PG1116+215, which implies a density of $102 \pm 16$ lines per unit redshift. The two-point
velocity correlation function of the Lyα clouds shows marginal evidence of clustering on \( \sim 500 \text{ km s}^{-1} \) scales, but only if the weakest lines are excluded. Tripp et al. also used the WIYN telescope to measure the redshifts of galaxies in the \( \sim 1^\circ \) fields centered on each QSO. They find 17 galaxy-absorber pairs within projected distances of 1 Mpc with velocity separations of 350 km s\(^{-1}\) or less. Monte Carlo simulations show that if the Lyα lines are randomly distributed, the probability of observing this many close pairs is \( 3.6 \times 10^{-5} \). Other statistical tests also indicate that the Lyα absorbers are not randomly distributed with respect to the observed galaxies. These observations suggest that many low-z Lyα clouds are due to gas in large-scale structures of galaxies rather than the gaseous halos of individual galaxies.

Savage, Tripp, and Lu have also completed a study of the O VI absorption line systems detected in the spectrum of H1821+643. Two O VI absorbers are observed toward this radio-quiet QSO, an intervening system and an “associated” system with \( z_{\text{abs}} \approx z_{\text{QSO}} \). Savage et al. analyze the physical conditions in these absorbers. They find that the intervening system could be photoionized by the UV radiation from background QSOs if the absorption arises in very low density diffuse gas with an extended distribution (the diameter of the absorber must be greater than 300 kpc). Alternatively, the O VI absorption lines could originate in collisionally ionized hot gas. Two galaxies are present at the redshift of the intervening O VI absorber with projected distances of 100 and 350 kpc. Therefore this O VI absorption could be due to the hot intracluster medium of a group of galaxies.

Tripp, Lu, and Savage have obtained a high signal-to-noise ground-based spectrum of the high-redshift QSO HS1700+6416 to study the metal absorption line systems. This QSO will be observed by the Space Telescope Imaging Spectrograph investigation team in 1998 in order to search for very highly ionized gas traced by species such as Ne VIII and Mg X, and the ground-based spectrum obtained by Tripp et al. will be crucial for the analysis of the HST data. Species such as Ne VIII are optimal for probing the distribution of hot gas in the vicinity of galaxy clusters and groups. This will provide an important test of cosmological hydrodynamic simulations which predict the presence of such hot gas regardless of the specific cosmology assumed.

Kepner, Tripp, T. Abel (Max-Planck-Institut), and Spergel have constructed detailed models of gas in small dark matter halos in order to predict their absorption line signatures for comparison to QSO absorption lines. The models include full radiative transfer and gas dynamics and show the effects of a multiphase absorbing medium since the mini-halo develops a self-shielded core as the UV background intensity decreases. They find that the absorption signatures of mini-halos are consistent with the observed absorption lines in many cases. However, this model cannot match the properties of the intervening O VI absorber
studied by Savage, Tripp, and Lu.

M. and T. Sugino (Tokyo) and Spergel propose that we may be able to detect $z > 10$ objects through their carbon, nitrogen and oxygen emission lines. By redshift of 10, star formation in the first objects should have produced considerable amounts of carbon, nitrogen and oxygen. The submillimeter lines of C, N and O redshift into the millimeter and centimeter bands (0.5 mm–1.2 cm), where they may be detectable. High spectral resolution observations could potentially detect inhomogeneities in C, N and O emission, and see the first objects forming at high redshift. They calculate the expected intensity fluctuations and discuss the frequency and angular resolution required to detect them. At $1 + z \sim 10$, the typical protogalaxy has a velocity dispersion of $30 \text{ km s}^{-1}$ and angular size of 1 arcsecond. If CII is the dominant coolant, then they estimate a characteristic line strength of $\sim 0.1 \text{ K km s}^{-1}$. If the intensity fluctuations are detected, they will probe matter density inhomogeneity, chemical evolution and ionization history at high redshifts.

2.5. Clusters and groups of galaxies

Bahcall, in collaboration with Cen and Fan, continued her investigation of the evolution of clusters of galaxies and the strong constraints that cluster evolution places on cosmological models. They showed that measuring the redshift evolution of the number density of rich clusters breaks the classical degeneracy between $\Omega$ (the mass density parameter of the universe) and $\sigma_8$ (the amplitude of mass fluctuations on $8h^{-1}\text{Mpc}$ scales), $\sigma_8\Omega^{0.5} \sim 0.5$, that follows from the present-day cluster abundance. Using the Press-Schechter approximation and cosmological simulations, they found that low-$\sigma_8$ models evolve exponentially faster than high-$\sigma_8$ models for a given cluster mass. The strong dependence on $\sigma_8$ arises because clusters represent rarer density peaks in low-$\sigma_8$ models. In contrast, the evolution rate at $z < 1$ is relatively insensitive to the density parameter $\Omega$ or to the exact shape of the power spectrum. Cluster evolution therefore provides a unique and powerful method to determine $\sigma_8$.

Bahcall and Fan then used the three most massive clusters of galaxies observed so far at $z > 0.5$ to constrain $\Omega$ and $\sigma_8$. They showed that the existence of such massive clusters ($\sim$twice the mass of Coma) at these early epochs—even the existence of the single most distant cluster at $z = 0.83$ (MS 1054-03), with its large gravitational lensing mass, high temperature ($\sim 12 \text{ Kev}$), and large velocity dispersion—is sufficient to establish powerful cosmological constraints. They find that high-density, $\Omega=1$ ($\sigma_8 \approx 0.5\text{–}0.6$) Gaussian models are ruled out by these data, since they predict $\sim 10^{-5}$ massive clusters at $z > 0.65$ ($\sim 10^{-3}$ at $z > 0.5$) instead of the 1 (3) clusters observed. They find best fit values of $\Omega = 0.2^{+0.3}_{-0.1}$.
Bryan, Norman and R. Sunyaev (Max-Planck-Institut) investigated the role of turbulence in X-ray clusters. They found that hierarchical models of structure formation generically predict turbulent velocities of roughly $400 \text{ km s}^{-1}$ in rich clusters. They showed that this would be difficult to detect through microwave or sub-mm observations of the kinematic Sunyaev-Zel’dovich effect, but should be clearly seen as an additional source of broadening in metal emission lines, which future missions, such as XMM, could detect.

Cen has used a large simulation of a realistic cosmological model (CDM with $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_0 = 0.4$, $\Lambda_0 = 0.6$, $\sigma_8 = 0.79$) to study projection effects on observables of clusters of galaxies, including richness, velocity dispersion, X-ray luminosity, total mass estimates (using the virial theorem, X-rays and lensing), gas fraction and substructure. The principal results include: (i) The average gas-to-mass ratio in clusters appears to be 30-40% higher than its actual value; moreover, the width of the observed distribution of this ratio is entirely accounted for by projection effects. The enhancement in gas-to-mass ratio due to projection is not quite sufficient to reconcile the standard nucleosynthesis value of $\Omega_{\text{baryon}}$ with $\Omega_0 = 1$ for any plausible value of $H_0$. (ii) Rich cluster masses derived from X-ray temperatures or galaxy velocity dispersions underestimate the true cluster mass by about 20% on average, with the former displaying a smaller scatter. Methods based on gravitational lensing overestimate the true mass by only 5–10% but have larger scatter than X-ray masses. It appears that projection effects alone may account for the discrepancies between various mass estimates for individual clusters. (iii) Projection inflates substructure measurements in galaxy maps, and most of the substructure observed in real clusters of galaxies may be due to projection. (iv) The X-ray luminosity of a cluster within a radius $1.0h^{-1}\text{ Mpc}$ is hardly altered by projection, rendering the cluster X-ray luminosity function a very useful and simple diagnostic for comparing observations with theoretical predictions. (v) The only meaningful way to compare predictions of a cosmological model with cluster observations is to subject clusters in a simulated universe to exactly the same observational biases and uncertainties, and to compare the “observed” simulated clusters with real ones.

Cen has proposed the correlation function of rich clusters of galaxies as a test of topological-defect cosmological models. Textures initially are randomly distributed on scales larger than their size, in sharp contrast to the initial high-density peaks in Gaussian models which are already strongly clustered before any gravitational evolution has occurred. One thus expects that the correlation of large cosmic objects such as clusters of galaxies in the texture model should be significantly weaker than its Gaussian counterpart. Cen shows that a texture model with $\Omega_0 = 1$ and bias $b = 2$ (as required by cluster abundance observations) predicts a correlation length $\leq 6h^{-1}\text{ Mpc}$ for clusters, independent of richness. On the other
hand, the observed correlation length for rich clusters is $\geq 10h^{-1}\text{Mpc}$. It thus appears that the global texture cosmological model or any random-seed cosmological models are ruled out at a very high confidence.

Cen, in collaboration with F. Governato (Durham), B. Moore (Durham), J. Stadel, G. Lake, and T. Quinn (Washington), has used the dynamics of the Local Group and its environment as a unique test of cosmological models. The velocity field within $5h^{-1}\text{Mpc}$ of the Local Group is extremely "cold": the deviation from a pure Hubble flow, characterized by the observed radial peculiar velocity dispersion, is only $\sim 60\text{ km s}^{-1}$. They compare the local velocity field with similarly defined regions extracted from N-body simulations of universes dominated by CDM. They find that neither $\Omega = 1$ nor $\Omega = 0.3$ CDM models can produce a single candidate Local Group that is embedded in a region with such small peculiar velocities: the typical dispersions are $300-700\text{ km s}^{-1}$ and $150-300\text{ km s}^{-1}$ respectively, several times the observed value.

Spergel, Refregier, and Vogeley initiated a project to study the effect of galaxies on their environment and, in turn, the impact of this environment on galaxy evolution, focusing on the most common structures in the universe: groups of galaxies and the filamentary network of large-scale structure which they trace. The velocity dispersion of groups and filaments is comparable to that of the galaxies themselves, thus interactions are frequent and the intragroup medium may be indistinguishable from the filamentary gas. The appearance of a variety of phenomena on these scales, including morphological segregation, variation of the dark matter to baryon ratio, and variation of metallicity, indicate that study of these regions is critical to understanding feedback between galaxies and their environment. The astrophysical origins of galaxy "biasing" and the diffuse X-ray background lie in this regime. Using both analytic methods and N-body/hydrodynamical simulations, they are studying energetics and dynamics in this setting and predicting observable relationships between galaxy and gas properties.

### 2.6. Gravitational lenses

Cen, Ostriker and J. Wambsganss (Potsdam) have developed a new ray-tracing method to study gravitational lensing by three-dimensional mass distributions. As an example, the method is applied to a standard CDM universe. The results include estimates of the frequency of multiply imaged quasars, the distribution of separations of multiple quasars, and the redshift distribution of lenses; all as a function of quasar redshift. The ultimate goal is to apply this method to a number of cosmogonic models and to eliminate models whose gravitational lensing properties are inconsistent with observations.
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 or OGLE) and related projects. All of the hardware and most of the software needed for OGLE was developed at Warsaw University Observatory, under the leadership of A. Udalski. The system became fully operational in January 1997. In the spring of 1998 a new “Early Warning System” was implemented. A total of 25 microlensing event candidates in the galactic bulge have been detected up to July 27. Considerable effort is devoted to bringing the OGLE data into the public domain as soon as practical, making heavy use of the Web.

The OGLE team, with Princeton graduate student P. Wozniak, confirmed the “short” distance (distance modulus 18.2) to the Large Magellanic Cloud using RR Lyrae variables and red clump giants.

Paczyński pointed out that the proposed Space Interferometry Mission (SIM) will be capable of determining the masses of the unknown halo objects responsible for gravitational microlensing events, and of measuring directly the masses of nearby, high proper-motion stars.

2.7. Gamma-ray bursts, active galactic nuclei, and black holes

The remarkable afterglow of the gamma-ray burst of 8 May 1997 (GRB 980508) was detected at X-ray, optical, and radio wavelengths. For the first time, absorption lines were seen, thus proving the cosmological distance of the afterglow and vindicating Paczyński’s claim that GRBs are at cosmological distances. Shortly after this discovery, J. Goodman pointed out that the radio source might show evidence of diffractive scintillation and that if so, this observation could provide an upper limit to the angular size of the source and hence a lower limit to its distance. Soon after Goodman’s prediction, Frail et al. announced radio flux variations that appear consistent with scintillation, implying a source size of a few microarcseconds and a relativistic expansion velocity at the time of the radio detection.

Paczyński pointed out that the known afterglows of gamma-ray bursts indicate that the bursts are located in or near star-forming regions. Several new positions point in the same direction, indicating that the bursts are related to violent deaths of young massive stars, and not to the mergers of old neutron stars. Neutron star mergers are likely to result not in bursts but rather in short optical transients.

Simple models developed by Li and Paczyński indicate that neutron star mergers are likely to result not in gamma-ray bursts but in optical transients located far from the centers
of their host galaxies. Recently such optical transients, with no apparent host galaxies, were discovered in deep supernova searches. These events may be related to neutron star mergers.

A. Ulmer (formerly a Princeton graduate student, now a postdoc at Max Planck Institut für Astrophysik), Paczyński, and Goodman have re-examined optically thick atmospheres formed from stars tidally disrupted by supermassive black holes. A. Loeb (Harvard) and Ulmer had concluded in 1997 that the effective temperature of such envelopes has a roughly constant universal value depending only weakly on the mass of the black hole. In the new study, the photospheric radius and effective temperature are shown to be extremely sensitive to an ill-determined inner boundary condition near the black hole. Nevertheless, the temperature has a minimum comparable to the previously proposed universal value and favorable for optical detection—about 6000 K. Remarkably, mild general-relativistic effects cause convection in such atmospheres.

A. H. Diercks, E. W. Deutsch (Washington), F. J. Castander, D. Q. Lamb (Chicago), C. Corson (APO), G. Gilmore (Cambridge), R. Wyse (Johns Hopkins) and Turner exploited the remote observing and fast instrument change capabilities of the Apache Point Observatory (APO) 3.5-meter telescope to obtain R-band and J-band light curves of an optical transient which is likely to be associated with the gamma-ray burst event GRB 971214. Their first measurement took place only 17 hours after the gamma-ray event. The brightness decayed with a power-law exponent of approximately $-1.2$, similar to but slightly steeper than those of two previous well observed events (GRB 970228 and GRB 970508). The transient decayed monotonically during the first four days following the gamma-ray event—this contrasts with the optical transient associated with GRB 970508, which peaked in brightness two days after the burst.

Turner has collaborated with A. Yonehara, S. Mineshige (Kyoto), J. Fukue (Osaka Kyoiku) and M. Umemura (Tsukuba) to study microlensing diagnostics of accretion disk structure. The optical/ultraviolet continuum from active galactic nuclei (AGN) seems to originate from optically thick and/or thin disks, and occasionally from associated circum-nuclear starburst regions. These different possible origins can, in principle, be distinguished by observations of gravitational microlensing events. They performed numerical simulations of microlensing of an AGN disk by a single star passing in front of the AGN. The calculated spectral variations and light curves show very different behavior for the different models: variability over a few months with strong wavelength dependence is expected in the case of an optically thick disk (standard model), while an optically thin disk (advection-dominated model) will produce shorter, nearly wavelength-independent variation. With a starburst region, much slower variations (over a year) are superimposed on the shorter variations.

Turner continued to work with A. Yonehara, S. Mineshige, T. Manmoto (Kyoto), J.
Fukue (Osaka Kyoiku), and M. Umemura (Tsukuba) to develop an X-ray microlensing probe of accretion disk structure in the gravitationally lensed quasar Q2237+0305. The innermost regions of the quasar can be resolved by a gravitational-lens “telescope” on scales down to a few AU. For this purpose, X-ray observations are ideal, because X-rays originate from the innermost regions of the disk. They performed numerical simulations of microlensing of a standard optically thick disk as well as an optically-thin, advection-dominated accretion flow. They find that X-ray radiation, which is produced in optically thin regions, exhibits intensity variation over a few tens of days. In contrast, optical-UV fluxes, which are likely to come from the optically thick region, exhibit more gradual light changes, which are consistent with the microlensing events so far observed in Q2237+0305. Currently, Q2237+0305 is being monitored for lensing events at APO. Once a lensing event begins, simultaneous multi-wavelength observations by X-ray satellites (e.g., ASCA, AXAF, XMM) as well as the Hubble Space Telescope (HST) could reveal an AU-scale central accretion disk around a black hole.

Blanton, Turner and J. Wambsganss (Potsdam) analyzed observations of the quadruply lensed quasar Q2237+0305 which they obtained with HST. On a timescale of 3–4 hours, they observed no variation in component A greater than 0.02 mag. The other components remain constant over a period of 10 hours to within about 0.05 mag. In the final 5 hours there is some evidence (not conclusive) for variation of component D by about 0.1 mag. Their results show that any fifth (central) component must be at least 6.5 mag fainter than component A. They also determined the astrometric properties of the lens system; their values are systematically larger than those of other investigators (by 0.1% to 2.0%), but there are reasons to believe that the new results are more reliable. The F336W filter was chosen for the observations because it corresponds to the redshifted Lyα line of the quasar. This filter might have allowed them to see extended Lyα emission from the broad-line region (BLR) of the quasar as Lyα arcs, and hence to determine the physical size of the BLR. However, the quasar components in this filter are consistent with a point source. They conclude that there cannot be any Lyα feature in the image plane brighter than about 23.5 mag in F336W and further from the quasar core than 100 mas. According to a lensing model by Rix, Schneider and Bahcall, this would preclude any such features in the source plane further than 20 mas (∼ 100h⁻¹ pc, assuming q₀ = 0.5) from the quasar core and brighter than 25 mag before magnification.

Aperiodic optical variability is a common property of AGNs, though the mechanism is still open to question. To study the origin of the optical-ultraviolet variability in AGNs, T. Kawaguchi, S. Mineshige (Kyoto), M. Umemura (Tsukuba) and Turner compared light curves of two models to observations of the quasar 0957+561. In the starburst (SB) model, the random superposition of supernovae in the nuclear starburst region produces aperiodic luminosity variations, while in the disk-instability (DI) model, variability is caused by insta-
bilities in the accretion disk around a supermassive black hole. They calculated fluctuating light curves and structure functions, $V(\tau)$, by Monte-Carlo simulations of the two models. Each resultant $V(\tau)$ possesses a power-law portion, $[V(\tau)]^{1/2} \propto \tau^\beta$, at short time lags $\tau$. The two models can be distinguished by their logarithmic slope, $\beta$; $\beta \sim 0.74–0.90$ in the SB model and $\beta \sim 0.41–0.49$ in the DI model, while the observed light curves exhibit $\beta \sim 0.35$. Therefore, the DI model is favored over the SB model in this case. In addition, they examined the time-asymmetry of the light curves by calculating $V(\tau)$ separately for brightening and decaying phases. The two models exhibit opposite trends of time-asymmetry to some extent, although the presently available light curve is not long enough to test this prediction.

### 2.8. Galaxies

Over the past five years the evidence that massive black holes are commonly found in the centers of inactive nearby galaxies has become extremely strong. S. Tremaine, working with J. Magorrian (CITA), K. Gebhardt and D. Richstone (Michigan), R. Bender (Munich), G. Bower, R. Green, T. Lauer (KpNO), A. Dressler (Carnegie), S. Faber (Santa Cruz), C. Grillmair (JPL), and J. Kormendy (Hawaii), has compiled the first large survey of the distribution of black-hole masses, using a sample of 36 galaxies with HST photometry and ground-based spectroscopy. They find that most galaxies contain central black holes whose typical mass is $\sim 0.6\%$ of the mass of the spheroidal stellar component of the galaxy; this result is entirely consistent with the requirement that accretion onto these objects is the power source for quasars and active galactic nuclei.

The same collaborative team has analyzed the structure of the centers of early-type galaxies, using a sample of 61 elliptical galaxies and spiral bulges with HST photometry. The photometric profiles are combined with ground-based data on central velocity dispersions, total luminosities, rotation velocities, and isophote shapes to explore correlations among these parameters. Luminous galaxies ($M_V < -20.5$) show core profiles, which have significant changes in their log-log surface-brightness profiles at a break radius $r_b$. Break radius and core luminosity are approximately proportional to the analogous global parameters, effective radius and total luminosity. Cores follow a fundamental plane that parallels the global fundamental plane but is 30% thicker; some of this extra thickness may be due to the effect of massive black holes on central velocity dispersion. Faint galaxies ($M_V > -22.0$) show steep, largely featureless power-law profiles that lack cores. The centers of power-law galaxies are up to $10^{4–5}$ times denser in mass and luminosity than the cores of large galaxies at a limiting radius of 10 pc. At intermediate magnitudes ($-22.0 < M_V < -20.5$), core and power-law galaxies coexist. Central properties correlate strongly with global rotation and
shape: core galaxies tend to be boxy and slowly rotating, whereas power-law galaxies tend
to be disky and rapidly rotating. At intermediate magnitudes, the presence of a core is a
better predictor of boxiness and slow rotation than absolute magnitude.

Ostriker and Tremaine investigated a longstanding paradox in galaxy dynamics: why
do galactic bars rotate with high pattern speeds, when dynamical friction should rapidly
couple the bar to the massive, slowly rotating dark halo? The paradox may be resolved by
considering the dynamical interactions between the galactic disk and inhomogeneities in the
dark halo. Plausible formation models lead to a halo composed largely of tidal streamers.
Dynamical friction between these streamers and the disk spins up and flattens the inner halo,
thereby quenching the dynamical friction exerted by the halo on the bar. At the same time
the halo heats and thickens the disk, perhaps forming a rapidly rotating bulge. More gener-
ally, gravitational scattering from tidal streamers or other phase-wraped inhomogeneities
represents a novel relaxation process in stellar systems, intermediate between violent relax-
ation and two-body relaxation, which can isotropize the distribution function at radii where
two-body relaxation is not effective.

C. Murali (CITA) and Tremaine have examined the response of a galaxy to slowly
varying gravitational perturbations, such as those due to external tidal fields. They have
focused on the singular isothermal sphere, which is not only a plausible model for a dark halo
but also admits near-analytic solutions for its linear response. For odd spherical harmonics,
the response is identical to the response of the analogous isothermal fluid system. For even
spherical harmonics, the response can be regarded as an infinite series of wavetrains in
\( \log r \), implying alternating compression and rarefaction in equal logarithmic radius intervals.
Partly because of the oscillatory nature of the solutions, tidal fields from external sources are
not strongly amplified by an intervening isothermal stellar system, except at radii \(< 10^{-3.5}\)
times the satellite radius; at some radii the stellar system can even screen the external tidal
field in a manner analogous to Debye screening.

J. Touma (Texas) and Tremaine have devised a symplectic map to describe the behavior
of eccentric orbits in cuspy triaxial potentials, such as those found near the centers of galax-
ies. The map correctly reproduces most of the features of the surface of section for orbits in
the non-axisymmetric logarithmic potential, including the presence of minor resonant fam-
ilies found by Schwarzschild ("fish", "bananas", etc.), but is \( \sim 10^3 \) times faster than orbit
integration.
2.9. Galactic astronomy and interstellar matter

Using OGLE data on the galactic bulge red clump stars, and the Hipparcos data on the nearby red clump stars (over 1000 with parallax errors less than 10%) Paczyński and his former student K. Stanek (Harvard) determined the distance to the Galactic Center to be $8.4 \pm 0.4$ kpc. This method was subsequently applied by various investigators to estimate distances to several nearby galaxies.

Paczyński found that the observed $V - I$ colors of red clump giants in the galactic bulge are not correlated with the published determinations of metallicity [Fe/H]. The reason for this puzzling result is not known, but low accuracy of the [Fe/H] determinations is a possibility. This problem has to be solved before the red clump giants can be used as reliable standard candles.

Draine has continued to work on the theoretical astrophysics of the interstellar medium, with particular attention to problems connected with the dynamics of interstellar dust grains, radiative transfer in X-ray irradiated gas, and the physics of photodissociation fronts.

The process of grain alignment, whether by radiative torques or the “classical” Davis-Greenstein mechanism of paramagnetic dissipation, characteristically involves “crossover” events, where the grain’s angular velocity component along the grain’s principal axis of largest moment of inertia changes sign. These crossover events are critical to the process of grain alignment, because the grain is easily disoriented during the period when its angular momentum is small. A. Lazarian and Draine have shown that previous analyses of the crossover process overlooked the subtle but very important effects of thermal fluctuations within the grain. When these fluctuations are taken into account, it is found that the larger grains—the ones which are observed to be highly aligned in the interstellar medium—are much less susceptible to disorientation during crossover than had previously been believed. As a result, it is found that even without radiative torques acting, classical paramagnetic dissipation appears capable of achieving the observed degree of grain alignment, for plausible assumptions regarding grain properties.

Draine and Lazarian 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 $100\mu$m emission from interstellar dust. They estimated the intensity of the rotational emission for various interstellar environments and discussed the physical processes involved in the rotational dynamics—these include 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.

Draine and Lazarian have examined the physics of thermal fluctuations in magnetic 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 the magnetization of the magnetic materials.

With W. Chiu (graduate student, Physics) Draine estimated the radiation pressure resulting from trapped Ly\(\alpha\) photons within a stellar atmosphere subject to X-ray irradiation, as would be the case for a star sufficiently close to an active galactic nucleus. This required assessment of the diffusion of resonance line photons, both in space and in frequency, to relate the Ly\(\alpha\) production rate to the Ly\(\alpha\) pressure. It is found that for low gravity stars (e.g., supergiants) the radiation pressure can approach \(\sim 20\%\) of the gas pressure. While a hydrostatic equilibrium exists for a plane-parallel atmosphere, it seems likely that the radiation pressure would have dramatic dynamical effects on a realistic stellar atmosphere subject to unidirectional X-ray irradiation.

Draine 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 Magellanic Clouds. 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 H\(_2\) in the stellar spectrum.

Lazarian worked with D. Pogosyan on the statistical description of galactic atomic hydrogen, relating the statistics of 21 cm intensity to the statistics of density and velocity. They showed that two distinctly different regimes of interferometric observations of HI exist. The first one (“thick slicing”) is sensitive to density fluctuations and the inversion suggested earlier by Lazarian is applicable to it. The other regime, which was called “thin slicing”, is sensitive to both velocity and density fluctuations and therefore the velocity and density statistics can be disentangled. In another paper Lazarian and Pogosyan studied how fluctuations of velocity deform filaments that are observed in atomic hydrogen and how the observed filamentary pattern depends on the spectrum of density and velocity.

Lazarian and P. Myers (Center for Astrophysics) studied the dynamics of molecular
clouds. This work was motivated by recent observations of cloud contraction, and showed that dissipation of Alfvén turbulence can account for the observed velocities.

Lazarian and M. Efroimsky (Harvard) examined inelastic relaxation within interstellar grains. This work was motivated by an earlier study by Lazarian and Draine where it was found that internal relaxation can substantially alter the efficiency of paramagnetic alignment. Lazarian and Efroimsky showed that it is impossible to treat grain deformations arising from grain precession using the formalism of acoustic modes and developed a new formalism that accounts for the nearly isothermal character of grain deformations. They have also modified their mathematical technique to account for adiabatic deformations of asteroids and comets and calculated the rates of internal dissipation for these bodies.

Jenkins and Sofia (Villanova) analyzed the 1048 and 1066 Å absorption features from interstellar neutral argon in the ultraviolet spectra of nine early-type stars observed by the Interstellar Medium Absorption Profile Spectrograph (IMAPS) in 1993. They found that for the stars ζ Pup, γ² Vel and β Cen, the abundance of argon to hydrogen is depleted with respect to the solar or B-star abundance ratio by the logarithmic reduction factors $D = -0.37 \pm 0.09$ dex, $-0.18 \pm 0.10$ dex and $-0.61 \pm 0.12$ dex, respectively. For the remaining stars, lower limits for $D$ were obtained. For the characteristically low-density lines of sight in this study, it is unlikely that argon can be depleted onto dust grains. Instead, Jenkins and Sofia argued that the relatively large photoionization cross section of neutral argon, compared to that of hydrogen, makes it much easier to hide in its ionized form within regions that are partially ionized. In regions that are about half ionized, this effect can lower Ar I/H I by $-0.11$ to $-0.96$ dex, depending on the energy of the photoionizing radiation and its intensity divided by the local electron density. They pointed out that the observed values of Ar I/H I could be a good discriminant between energetic photons and electron collisions as a source of ionization in H I regions that are partially ionized.

Jenkins measured the thermal pressure of the medium inside the Local Bubble [a region that contains mostly hot ($\sim 10^6$ K) gas out to a radius of $\sim 100$ pc from the Sun] by analyzing absorption features of C I in the spectrum of δ Cyg ($l = 79^\circ$, $b = +10^\circ$, $d = 52$ pc) recorded by the GHRS echelle spectrograph on HST. The fine-structure levels in the ground electronic state of C I can be excited by collisions, and from the population ratios of these states Jenkins derived a thermal pressure range $10^{2.7} < p/k < 10^{3.7}$, a value that is lower than results reported by other investigators based on EUV emission by the hot gas in front of cold clouds embedded in the Local Bubble.

HST Early Release Observations of the spectrum of HD72089 recorded at a resolving power of $\lambda/\Delta \lambda = 110,000$ for the Space Telescope Imaging Spectrograph (STIS) investigation team were analyzed by Jenkins, Tripp and E. Fitzpatrick. This star is located behind
gases that have been accelerated by shocks within the Vela supernova remnant. They identified seven narrow components of C I, some of which showed significant levels of fine-structure excitation. Absorption features from C II, N I, O I, Si II, S II and Ni II appeared over a heliocentric velocity range from $-70$ to $+130$ km s$^{-1}$. The analysis of the abundances of these species indicates that some elements may be preferentially ionized to higher stages by photoionizing radiation emitted by hot gas immediately behind the shock fronts. This effect may explain the remarkably low abundances of N I and O I.

Jenkins also collaborated with the STIS team in an interpretation of interstellar features appearing in the O-type star CPD $-59^\circ2603$ in the Carina Nebula, again taken from Early Release Observations. This investigation identified a heterogeneous collection of species, including CO molecules, atoms in low and high stages of ionization, and features arising from atoms at high velocity. The investigation derived some properties of accelerated gases within the nebula, as well as material residing in foreground H I and H II regions. The most conspicuous features were the Mg I and Mg II profiles that showed many components over a heliocentric velocity range $-235 < v < +123$ km s$^{-1}$.

L. Blitz (Berkeley), P. Teuben (Maryland), Dap Hartman and W. Butler Burton (Leiden) and Spergel have suggested that the high–velocity clouds (HVCs) are large clouds, with typical diameters of 25 kpc and containing $5 \times 10^7$ solar masses of neutral gas and $3 \times 10^8$ solar masses of dark matter, falling onto the Local Group; altogether the HVCs contain $10^{11}$ solar masses of neutral gas. Their reexamination of the Local-Group hypothesis for the HVCs connects their properties to the hierarchical structure formation scenario and to the gas seen in absorption towards quasars. They interpret the more distant HVCs as dark matter “mini–halos” moving along filaments towards the Local Group. Most poor galaxy groups should contain HI structures to large distances bound to the group. The HVCs are local analogues of the Lyman–limit clouds. Their analysis of the HI data leads to the detection of a vertical infall of low-velocity gas towards the plane. This implies that the chemical evolution of the Galactic disk is governed by episodic infall of metal-poor HVC gas that only slowly mix with the rest of the interstellar medium. The Local–Group infall hypothesis makes a number of testable predictions: the HVCs should have sub-solar metallicities; their H$\alpha$ emission should be less than that seen from the Magellanic Stream; the clouds should not be seen in absorption to nearby stars; and the clouds should be detectable in both emission and absorption around other groups.

Knapp reviewed cold gas and star formation in elliptical galaxies at the “Star Formation in Early-Type Galaxies” conference in Guanajuato. A significant fraction of elliptical galaxies not in dense clusters is now known to contain interstellar matter in all the familiar phases—hot, warm and cold gas. The cold gas content of elliptical galaxies is $< 1\%$ to about $10\%$ of the
amounts found in spiral galaxies. In many elliptical galaxies, cold gas is concentrated to the inner regions and has surface densities comparable to, or greater than, the regions of highest star formation in the Galactic disk. The compact disks seen in the inner regions of some elliptical galaxies may form from these clouds; however, the relative cold gas content shows no statistical correspondence with galaxy morphology—core morphology, boxiness/diskiness, or luminosity. The cold and hot (X-ray emitting) gas masses in elliptical galaxies are found to be anticorrelated. The observations show that in a statistical sense typical field elliptical galaxies contain a small amount of cold interstellar matter: this is more consistent with a long-lived, evolving interstellar medium than with recent capture of the gas.

### 2.10. Stellar systems

With S. S. Kim and H. M. Lee (Pusan), J. Goodman has examined the effect of a mixture of stellar masses on the dynamical evolution of globular clusters after core collapse. Two components suffice to represent the stars most common near the core: main-sequence stars at the turnoff and evolved degenerates. If the degenerates are individually more massive than the normal stars and comprise a few percent or more of the total cluster mass, then they dominate the core after core collapse and heat the cluster by three-body processes. Scaling laws for half-mass quantities are derived and confirmed by Fokker-Planck calculations. In agreement with speculations made by Goodman in 1993, the Fokker-Planck results show that two-component systems are stabler to gravothermal oscillations than single-component models, and that the critical parameter for gravothermal instability in postcollapse is the ratio of the core and total cluster energies divided by the ratio of central to half-mass relaxation times.

Goodman and former Princeton graduate student E. Dickson have studied the inexplicably rapid circularization of close main-sequence late-type binaries. This is usually attributed to turbulent convective viscosity acting on the equilibrium tide, but a previous paper by Goodman and Oh showed that the convective mechanism is inadequate. The new study examines the role of tidally excited g-modes at the base of the convection zone, a mechanism often invoked for early-type binaries but considered uninteresting for late types because of the difficulty of damping the g modes in the radiative core. Goodman and Dickson show that evolution of the resonant g-mode frequencies and perhaps also nonlinear wave steepening near the center of the core can solve the damping problem. Even with efficient damping, however, the tidal coupling is only strong enough to circularize binaries out to periods of about six days on the main sequence, whereas observations indicate circularization out to at least twelve days.
R. Nelson (Caltech) and Tremaine have applied linear response theory and the fluctuation-dissipation theorem to stellar systems, to clarify the relation between fluctuating gravitational forces and dynamical friction without using traditional approximations such as local forces, instantaneous collisions, neglect of self-gravity, small-angle deflections, etc. For isothermal stellar systems, they derive an expression for the instantaneous dynamical friction force, in terms of the correlation function of fluctuating forces, that does not require any of these approximations.

2.11. Stars

Knapp, K. Young (Center for Astrophysics), E. Lee (graduate student), and A. Jorissen (Brussels) began a survey of thermal molecular line emission from the envelopes of evolved mass-losing AGB stars to investigate a new phenomenon: the presence of two winds with different expansion velocities. CO(2-1) and CO(3-2) line emission was observed for 45 AGB stars at high velocity resolution. Double winds are found in 20% of the sample, and highly asymmetric lines are found in six other stars. The data tentatively suggest that double winds occur when the star undergoes a change (pulsational mode, chemical composition) and that the narrow components represent the onset of a new phase of mass loss.

G. Wallerstein (Washington) and Knapp reviewed the subject of carbon stars. The review discusses spectral classification, distances and luminosities derived from the Hipparcos catalog, scale height, effective temperatures, radii, molecular envelopes, mass-loss rates, abundances, and the properties of special carbon stars such as the carbon dwarfs, R stars, and CH stars.

Ž. Ivezić and Knapp expanded the recent Jorissen and Knapp (1997) study of S stars by including a detailed analysis of IRAS LRS data and variability properties. The distribution of dust emission features in the 8-23 micron region, and distribution of variability types (Miras vs. SRb/Lb) both follow the Jorissen and Knapp classification scheme based on five regions in color-color diagrams. Although S stars show a greater variety of dust emission features than O and C stars do, there is no firm evidence that S stars are significantly different regarding their evolutionary status. The properties of their infrared emission, mass-loss rates and outflow velocities are no more different from those for O and C stars than what would be expected because of somewhat different grain chemistry. They also find that differences between S type Miras and SRb/Lb variables are the same as the corresponding differences for O and C stars. Observed properties of O, C and S Miras closely agree with those expected for a steady-state radiatively driven wind, while SRb/Lb variables show an indication for a decrease of mass-loss rate during last several hundred years. It cannot be ruled out that the
mass-loss rate is changing periodically on comparable time scales, implying that the stars oscillate between the Mira and SRb/Lb phases during their AGB evolution as proposed by Kerschbaum et al. (1996). Such a possibility appears to be supported by recent HST images of the Egg Nebula obtained by Sahai et al. (1997), and the discovery of multiple CO winds by Knapp et al. (1998).

Ivezić, Knapp, and M. Elitzur (Kentucky) have calculated detailed self-consistent models of radiatively driven stellar outflows which couple the radiative transfer and hydrodynamics equations. The circumstellar envelope, which consists of gas and dust, is described as a two-component fluid to account for relative drifts. Their results agree well with both molecular line observations and infrared continuum spectra, thus providing strong evidence that outflows around cool luminous late-type stars are radiatively driven.

Ž. Ivezić has continued to work in collaboration with Elitzur on the scaling properties of the dust radiative transfer. Together with A. Miroshnichenko (Pulkovo) and D. Vinković (Kentucky), they apply their results to the studies of medium- and high-mass young stellar objects (e.g. Herbig Ae/Be stars, B[e] stars). In particular, they propose a simple resolution of inconsistencies encountered when constraining the geometry of dust around such stars. Spherical envelopes seem to be ruled out by submm observations which imply visual optical depths of about 1000, yet the stars are visible at optical wavelengths. Similarly, an alternative proposal invoking geometrically thin and optically thick disks cannot explain the existence of silicate emission feature. Furthermore, neither model is capable of explaining why for some sources the observed IR sizes decrease with wavelength. Ivezić and collaborators show that an alternative model involving both a spherical dusty envelope in free fall and an embedded optically thick and geometrically thin disk can explain all available observations. In particular, the puzzle of observed sizes decreasing with wavelength is resolved as 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.

### 2.12. Planetary systems

One of the most remarkable features of the planets that have recently been discovered around nearby stars is that they are found at small orbital radii—in some cases less than 10% of the Earth’s—where gas giant planets are not expected to form. Working with N. Murray and B. Hansen (CITA) and M. Holman (Center for Astrophysics), Tremaine has argued that these planets may have formed at much larger radii and then migrated inward to their current orbits; the migration is caused by gravitational scattering of residual planetesimals
and appears to be inevitable in a system whose protoplanetary disk is 10–100 times more massive than our own. Such massive disks are plausible but not yet directly observed.

L. Malyshkin (graduate student) and Tremaine have examined the evolution of highly eccentric, planet-crossing orbits in the restricted three-body problem (Sun, planet, comet). Following such orbits for the lifetime of the solar system using conventional integration techniques is a challenging task, because of accumulated numerical errors and the large CPU time required. They examined a simpler toy problem capturing most of the relevant physics: a symplectic map in which the comet energy changes instantaneously at perihelion, by an amount depending only on the azimuthal angle between the planet and the comet at the time of perihelion passage. This approximate but very fast mapping allowed them to explore the evolution of large ensembles of long-period comets, and to compare their results on comet evolution with those given by the diffusion approximation and by direct orbit integration of comet orbits. They found that at long times the number of surviving comets is determined by resonance sticking rather than a random walk; this result greatly enhances the number of primordial Neptune-crossing planets that might still be present in a scattered cometary disk.

One of the most exciting results in planetary science in the 1990s was the discovery of the Kuiper belt. By now over 60 Kuiper belt objects have been discovered; these are \( \sim 100 \text{ km} \) sized bodies (comets? planetesimals?) orbiting in a disk outside Neptune. Discovering these objects and tracking them are two quite different tasks; without follow-up observations to recover and track the objects over several seasons and determine their orbits, most will be lost. Tremaine, B. Gladman (CITA), M. Holman (Center for Astrophysics), W. Offut (Cloudcroft), B. Gillespie, C. Hastings, and K. Gloria (APO) experimented with using the APO 3.5-meter telescope for this purpose; they successfully recovered 4 Kuiper-belt objects with magnitude as faint as \( R = 23.3 \pm 0.5 \).

2.13. Magnetic Reconnection

Lazarian and Vishniac (Center for Astrophysics) studied magnetic reconnection. They found an increase of the reconnection rates (as compared to the Sweet-Parker rates) when magnetic fields are frozen into partially ionized gas. This increase is not sufficient to account for the magnetic diffusivity required by contemporary dynamo theories, but is important for magnetic cloud evolution in the interstellar medium. For instance, it can enable an efficient detachment of the collapsed core from the large scale galactic magnetic field. As a separate project Lazarian and Vishniac studied magnetic reconnection in the presence of tearing modes. They found that the reconnection velocity scales as \( Rm^{-1/3} \), where \( Rm \) is the
magnetic Reynolds number, while $Rm^{-1/2}$ is the prediction of Sweet-Parker theory.

R. Kulsrud and his students D. Uzdensky and T. Carter have continued to study magnetic reconnection as a fast magnetohydrodynamic process, in collaboration with an experimental study of the creation and merging of two plasma tori. There are two established, and competing, theories for the process: the Sweet-Parker theory and the Petschek theory. In order to properly decide between them it is necessary to study not only the reconnection layer itself, but the separatrix layer into which the reconnected plasma must flow. They assume that the separatrix layer is infinitely conducting and under this assumption they find that the flow in it can be treated independently of what happens as the reconnected lines merge into the downstream equilibrium region. For all possible initial conditions for the plasma in the layer they find that the reconnection rate is invariably the Sweet-Parker rate.

The results of the simulations seem to contradict a generally accepted result due to Cowling and Priest that the field lines at the very center of the reconnection region must osculate rather than cross at a finite angle. We show that this is due to an unwarranted assumption about the analyticity of the solution, and when this is corrected the results are consistent with the numerical simulations. Also this earlier Cowling-Priest result was extended by Shivamoggi to include a small resistivity and again the result was inferred to be osculating fields as the viscosity went to zero. However, again the conclusion was wrong since in this limit a boundary layer develops which vitiates the conclusion. The behavior of the boundary layer as viscosity goes to zero is identical with numerical simulations carried out in the same limit.

The rather slow reconnection rate predicted by Sweet-Parker seems at variance with the detailed X-ray pictures of solar flares observed with the Soho and Yohcoh satellites. It also is considerably slower than observed in the laboratory experiment where the reconnection layer was measured to be thicker than that predicted by their theory. However, in both cases it can be shown that conditions for normal resistivity are violated since for the predicted current density of Sweet and Parker the critical current for excitation of plasma waves is exceeded. The plasma waves that one expects to be excited produce anomalous resistivity that can be expected to explain most of the discrepancy with the Sweet-Parker theory.

2.14. Instrumentation and Software

The Princeton SDSS software group (R. Lupton, Strauss, Ivezić, Fan, Gunn and Knapp) have as their prime responsibility the photometric pipeline that automatically reduces the
data from the imaging camera on the SDSS 2.5-meter telescope. Observations with the imaging camera consist of continuous drift scans, with the sky passing through five filters in turn. These images are cut into a series of frames and the data from a given area of the sky are aligned; this is done by the “serial stamp collecting” pipeline, SSC. The set of five frames for a given field is analyzed by the Frames pipeline, which carries out the most computationally intensive parts of the reduction, the finding and measuring of objects.

Frames corrects the images for defects, cosmic rays and bad columns by interpolation, subtracts the bias, flat-fields the data, finds objects, measures them (position, brightness, size, shape, morphology), and classifies them (assigning a set of likelihoods that the image shape fits a suite of models—these likelihoods, plus priors, are the information on which star-galaxy separation is based). Frames then “deblends” overlapping objects, and writes out an object catalogue, a set of small cutouts (“atlas images”) in each of the five bands for every detected object, the corrected frames, masks for image defects and saturated pixels, and binned images with the objects subtracted.

The positions (on the CCD) and the instrumental brightnesses are then converted to position on the sky and magnitude using astrometric calibrations from the astrometric array and photometric calibrations from a small telescope (the “Monitor Telescope”). These calibration data are reduced through their own software pipelines (“Astrom”, the responsibility of the U.S. Naval Observatory, and “MTpipe”, the responsibility of Fermilab). Frames also cuts atlas images at the positions of objects in catalogues at other wavelengths (X-ray, radio, etc.) to aid in their optical identification. Lupton is in charge of the Frames pipeline and responsible for most of the code.

The Frames pipeline needs calibration data (point-spread function characteristics, bias vector, flat field vectors, sky brightnesses) as input; these need to be determined for the entire run and continuous from frame to frame. The Postage Stamp Pipeline (PSP) determines these quantities for an entire run, and interpolates them to the center of each frame. As well as cutting and aligning the frames, the SSC cuts subimages (“postage stamps”) at the positions of bright stars found in the astrometric array (thereby helping tie the astrometric, as well as photometric, solutions to the frames). PSP analyzes these stamps; it selects stars and calculates the mean point-spread function for a frame; this includes a calculation of the scattering wings. The PSP also calculates the sky levels for an entire run. Ivezić is responsible for both SSC and PSP.

The photometric pipeline has been under development for about seven years, first at Fermilab and later at Princeton. It is required to reduce the data at essentially the rate at which it is taken, 4.6 MB s⁻¹ (the current performance is within a factor of two of this goal). To aid the development process extensive simulations of the SDSS data have been
carried out over the years at Fermilab, and drift-scan data were taken during several nights in September 1997 using the APO 3.5-meter telescope and the University of Washington camera “SPICam” with a set of SDSS filters.

Following first light for the SDSS camera in May 1998, test data taken with the camera are now being reduced using this software, to test integration of the different pipelines, and measure the astrometric and photometric accuracy.

The data are also being examined at Princeton by the above group, aided by M. Vogeley, D. Schlegel, and a group of undergraduate summer students: J. Pepper, J. Goldston, A. McDaniel, D. Freedman and K. Finlator. Sample tests include: examining the PSF and its effect on image classification and deblending; examining galaxy classification and the measured magnitudes for galaxies; determining the sky brightness, limiting magnitude, camera/telescope throughput and image quality, to investigate whether these meet expectation and/or design; comparing SDSS data with those taken by other imaging telescopes; investigating the distribution of stellar colors and brightnesses to see if these are consistent with known data and Galaxy models and to investigate selection criteria for spectroscopic observations of various types of standard stars and of quasars; producing tools to monitor the quality of the data flow and of the reductions. This examination of the data by SDSS scientists has already produced several science results: new clusters of galaxies, new low surface brightness systems, and several new quasars.

In addition, Lupton is helping develop and finish the software which operates and monitors the SDSS instruments; Strauss is responsible for the independent testing of the spectroscopic pipeline, which is being written by scientists at the University of Chicago; Ivezić and Goldston are working with Fermilab astronomers on the photometric calibration software (MTpipe), and on calibrating the recently acquired photometric data.

The SDSS consortium consists of the University of Chicago, the Fermi National Accelerator Laboratory, the Institute for Advanced Study, the Japan Participation Group (a group of scientists from the University of Tokyo), the Johns Hopkins University, Princeton University, the U.S. Naval Observatory and the University of Washington.

Jenkins, Tripp, Wozniak, Sofia (Villanova) and Sonneborn (Goddard) have completed most of the data analysis software for high-resolution UV spectra of bright, early-type stars recorded by the Interstellar Medium Absorption Profile Spectrograph (IMAPS) which flew on the ORFEUS-SPAS II mission in November and December of 1996. Major accomplishments in this effort included the corrections for image distortions, derivations of wavelength scales, determinations of background levels from various sources, and the creation of routines to accomplish optimum extractions of the slightly overlapping echelle orders. The only
remaining uncompleted task is the creation of routines that can predict image shifts caused by changes in the Earth’s magnetic field. These shifts can be detected and compensated when the spectra of bright stars are processed, but the prediction scheme is needed for stars that are too faint to show features in individual frames.

Reale (electronics engineer) and Jenkins are developing circuitry to enable the real-time detection of photoevents in image frames coming from the windowless, electron-bombarded, intensified CCD image sensor that flew on IMAPS. This new capability will enable IMAPS to record spectra of faint stars with a signal-to-noise ratio that is not degraded by the CCD read noise. On previous missions, the image information was accumulated by straight addition of the analog signals from the video frames. This mode is all right for bright stars, but the spectra of fainter stars become lost in the CCD read noise if the photoevents are not explicitly recognized before the signals are combined. The development of a photon detection capability for this far-UV sensor should also be of potential benefit to experiments other than IMAPS.

As a member of the Space Telescope Imaging Spectrograph (STIS) team, Jenkins has been involved in the effort to make STIS operate at its full potential. In particular, he has evaluated the prospects of artificially suppressing the large dark count rate for the near-UV MAMA detector by temperature cycling. This scheme may be implemented after a cooler is installed during the third servicing mission for HST, thus enabling this detector to record better quality spectra of faint sources in the near-UV band.

Flux estimates for faint sources or transients are systematically biased high because there are far more truly faint sources than bright. D. W. Hogg (Institute for Advanced Study) and Turner have developed a maximum-likelihood method to correct for this effect as a function of signal-to-noise ratio and the (true) slope of the number-flux relation. The implications of these corrections for analyses of surveys are substantial; the most important is that sources identified at signal-to-noise ratios of four or less have essentially unknown fluxes.

C. Alard (Paris Observatory) and R. Lupton have developed new photometric software to detect variable sources, based on the “image subtraction” concept, which offers substantial advantages over conventional methods based on source fitting. This software will be implemented in the automated OGLE data pipeline.

Spergel belongs to a collaboration led by J. Mather that is exploring the possibility of developing a Far-Infrared Space Interferometer. In light of recent technical advances it is now practical to consider the possibility of placing a far-infrared interferometer in orbit early in the next century. Such a mission would provide unprecedented access to the far-IR (50–300
microns) at high spatial resolution, enabling studies of primordial gas clouds collapsing to form the first galaxies, the chemical evolution of the universe, and detailed observations of dust-enshrouded Galactic protostars, star-forming regions in nearby galaxies, and AGNs.

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