ITALIAN PHYSICAL SOCIETY

PROCEEDINGS

OF THE

INTERNATIONAL SCHOOL OF PHYSICS

«ENRICO FERMI»

COURSE CXXXII

edited by S. BONOMETTO, J. R. PRIMACK and A. PROVENZALE

Directors of the Course

VARENNA ON LAKE COMO

VILLA MONASTERO

25 July - 4 August 1995

Dark Matter in the Universe

1996

IOS Press

Ohmsha

AMSTERDAM, OXFORD, TOKYO, WASHINGTON DC

INDICE

S. BONOMETTO, J. R. PRIMACK and A. PROVENZALE – Introductory note .... pag. XVII

Gruppo fotografico dei partecipanti al Corso .... fuori testo

J. R. PRIMACK – Status of cosmological parameters: $\Omega_0 \approx 0.3$ *vs.* $\Omega = 1$.

1. Introduction .... pag. 1
2. Models with mostly cold dark matter .... » 2
3. Age of the Universe t_0 .... » 4
4. Hubble parameter H_0 .... » 6
   4·1. *A*) Relative-distance methods .... » 6
   4·2. *B*) Fundamental-physical approaches .... » 7
   4·3. Correcting for Virgocentric infall .... » 8
5. Cosmological constant Λ, and t_0 again .... » 9
6. Measuring Ω_0 .... » 11
   6·1. Very-large-scale measurements .... » 11
   6·2. Large-scale measurements .... » 12
   6·3. Measurements on scales of a few Mpc .... » 13
   6·4. Estimates on galaxy halo scales .... » 14
7. Clusters .... » 15
   7·1. Cluster baryons *vs.* big-bang nucleosynthesis .... » 15
   7·2. Cluster morphology .... » 17
   7·3. Cluster evolution .... » 17
8. Early structure formation .... » 18
9. Neutrino mass .... » 19
10. Conclusions .... » 20

OBSERVATIONAL DATA

R. P. KIRSHNER – Galaxy redshift surveys.

1. Introduction .... » 33
2. Redshift surveys .... » 36

3. The Las Campanas Redshift Survey .... pag. 38
4. The beginning of the end? .... » 41
5. Beyond the LCRS .... » 46

R. GIOVANELLI – Peculiar motions and the Tully-Fisher relation.

1. Introduction .... » 49
2. Newtonian theory of small perturbations .... » 50
3. The case for large-scale motions .... » 53
   3·1. The CMB dipole .... » 53
   3·2. Motions at the Local Supercluster scale .... » 53
   3·3. The Great Attractor .... » 54
   3·4. Bulk flows .... » 55
4. The Tully-Fisher relation .... » 56
   4·1. Scaling laws .... » 56
   4·2. Extinction and the TF relation .... » 57
   4·3. Optical and radio velocity widths .... » 59
   4·4. The scatter in the TF relation .... » 60
   4·5. Importance of the TF template relation .... » 61
5. Results for a cluster sample .... » 63
6. An all-sky field spiral sample .... » 66

M. P. HAYNES – Galaxy redshift surveys: caveat emptor.

1. Introduction .... » 71
2. Catalogs: tricks and pitfalls .... » 72
   2·1. Nearby-galaxy catalogs .... » 73
      2·1.1. Optical catalog .... » 74
      2·1.2. IRAS galaxy surveys .... » 76
   2·2. The density field based on redshift catalogs .... » 77
   2·3. Morphological and luminosity segregation .... » 77
3. The Pisces-Perseus Supercluster .... » 78
   3·1. Not a random volume .... » 78
   3·2. Measures of clustering .... » 83
   3·3. Morphological segregation .... » 85
   3·4. Substructure in clusters: Abell 2634 .... » 86
4. Hidden galaxies .... » 86
5. Conclusion .... » 89

E. L. WRIGHT – CMBR observations: spectrum.

1. Introduction .... » 91
2. Spectrum observations prior to COBE .... » 92
3. COBE mission .... » 93
4. DIRBE measurements .... » 94
5. FIRAS measurements .... » 95
6. Comparison of FIRAS with other data .... » 101
7. Possible distortions .... » 102
8. Summary .... » 104

E. L. WRIGHT – CMBR observations: anisotropy.

1. Introduction .... pag. 107
2. History .... » 108
3. The COBE DMR .... » 108
3·1. DMR data analysis. Sparse matrix .... » 109
3·2. Correlated noise in the DMR maps .... » 110
3·3. Scaling to large maps .... » 111
4. DMR results .... » 112
5. Galactic interference .... » 113
6. Power spectrum .... » 116
7. Comparison to large-scale structure .... » 119
8. Future CMB work .... » 119

A. CAMPOS – Galaxy number counts.

1. Introduction .... » 123
2. Modelling the number counts .... » 124
3. Luminosity evolution models .... » 126
4. The redshift distributions of faint field galaxies .... » 129
5. Could we fit the counts in a $q_0 = 0.5$ Universe model? .... » 131
6. Conclusion .... » 134

S. CRISTIANI – Cosmological adventures in the Lyman forest.

1. Introduction .... » 137
2. A Lyman-α database .... » 140
3. The b-N_{HI} distributions: the temperature of the Lyman-α clouds .... » 140
4. The HI column density distribution .... » 142
5. The redshift distribution .... » 144
6. The measure of the ultraviolet background from the proximity effect .... » 145
7. Clustering properties of the Lyman-α clouds .... » 147
8. Simulations .... » 151

ADVANCED STATISTICAL ESTIMATORS

A. DEKEL – Cosmic velocity fields.

1. Introduction .... » 157
2. Gravitational instability .... » 159
3. Measuring peculiar velocities .... » 162
3·1. Distance indicators .... » 162
3·2. Malmquist biases .... » 164
3·3. Homogenized catalogs .... » 166
4. Analysis of observed peculiar velocities .... » 167
4·1. Toy models .... » 167
4·2. Potential analysis .... » 169
4·3. Regularized multiparamenter models—Wiener filter .... » 171
4·4. Malmquist-free analysis .... » 172
4·5. Fields of velocity and mass density .... » 173

5. Predicted motions from the galaxy Z-distribution .... pag. 175
6. Testing basic hypotheses .... » 178
   6·1. CMB fluctuations *vs.* motions .... » 178
   6·2. Galaxies *vs.* dynamical mass .... » 179
   6·3. Environmental effects: ellipticals *vs.* spirals .... » 181
7. Then initial fluctuations .... » 183
   7·1. Power spectrum—dark matter .... » 183
      7·1.1. Bulk velocity .... » 183
      7·1.2. Mach number .... » 185
      7·1.3. Power spectrum from POTENT .... » 186
      7·1.4. Power spectrum from likelihood analysis .... » 187
   7·2. Probability distribution—back in time .... » 189
8. The value of Ω .... » 191
   8·1. β from galaxies *vs.* the CMB dipole .... » 192
   8·2. β from galaxy density *vs.* velocities .... » 193
   8·3. β from distortions in redshift space .... » 195
   8·4. Ω from PDFs using velocities .... » 197
   8·5. Ω from velocities in voids .... » 198
9. Discussion: are the hypotheses justified? .... » 200

S. BORGANI – Advanced statistical methods for large-scale structure studies.

1. Introduction .... » 209
2. The correlation statistics .... » 210
   2·1. Correlation functions .... » 211
   2·2. Correlations of a Gaussian field .... » 213
   2·3. The count-in-cell statistics .... » 215
   2·4. The hierarchical model .... » 219
3. Error analysis .... » 220
   3·1. Sampling errors .... » 220
   3·2. Cosmic variance .... » 221
4. Results from observations .... » 222
   4·1. Correlation analysis .... » 222
   4·2. The probability density function .... » 225
5. Geometrical descriptions of the LSS .... » 228
   5·1. The void probability function .... » 228
   5·2. Topology .... » 231
6. Conclusions .... » 234
Appendix A – The functional derivative .... » 235

P. COLES – Models of nonlinear clustering.
I. - Interesting distribution functions.

1. Introduction .... » 239
2. Continuous random fields .... » 240
   2·1. Statistical description .... » 240
   2·2. Gaussian random fields .... » 241
   2·3. Scaling and the Edgeworth expansion .... » 243

3. The lognormal model ... pag. 244
   3·1. Properties ... » 244
   3·2. Motivation ... » 245
4. Discrete distributions ... » 247
   4·1. Statistical description ... » 247
   4·2. The Poisson model ... » 248
   4·3. The GQED distribution ... » 249
5. Conclusions ... » 151

V. J. MARTINEZ – Measures of galaxy clustering.

1. Introduction ... » 255
2. Surveys of galaxy redshifts ... » 255
   2·1. Galaxy obscuration ... » 256
   2·2. Brightness and apparent-magnitude limit ... » 256
   2·3. Redshift pace distortions ... » 258
   2·4. Segregation ... » 258
   2·5. Ergodic hypothesis ... » 259
3. Statistical measures ... » 259
   3·1. Second-order characteristics ... » 259
   3·2. Estimators of $\xi(r)$ ... » 260
   3·3. Moments of the cell counts and scaling ... » 261
   3·4. Multiscaling ... » 262
4. Conclusions ... » 265

J. R. PRIMACK – Improved ways to compare simulations to data.

1. Introduction ... » 269
2. Testing models ... » 270
   2·1. Very large scales ... » 270
   2·2. Large-scale structure (~ (10–100) Mpc) ... » 272
   2·3. Intermediate scales (less than 10 Mpc) ... » 272
3. Large-scale constrained realizations ... » 274
4. Early structure formation ... » 275
5. Needs for the future ... » 276

J. SCHMALZING, M. KERSCHER and T. BUCHERT – Minkovski functionals in cosmology.

1. Motivation ... » 281
2. Fundamentals ... » 282
   2·1. Hadwiger's theorem ... » 282
   2·2. The principal kinematical formula of integral geometry ... » 284
   2·3. Minkowski functionals of a Poissonian distribution ... » 284
   2·4. Clusters, walls and filaments ... » 286
3. Applications ... » 286
   3·1. Simulations ... » 287
   3·2. Redshift catalogues ... » 288
4. The software and its future ... » 290

FROM BB TO MATTER-RADIATION DECOUPLING

E. W. KOLB – Inflation.

1. Preliminary—The art of inflation	pag.	295
2. Introduction—Why inflate?	»	297
2·1. Fine tuning in the big-bang model	»	298
2·2. Origin of perturbations beyond the Hubble radius	»	299
2·3. Unwanted relics	»	300
2·4. Accelerated expansion and entropy production	»	302
3. Models of inflation	»	302
3·1. No-roll inflation	»	302
3·2. Slow-roll inflation	»	304
3·2.1. Pre-history	»	304
3·2.2. The classical era of old inflation	»	305
3·2.3. Slow-rollover renaissance of new inflation	»	307
3·2.4. Rococo inflation	»	308
3·2.5. Impressionism	»	308
3·2.6. The postmodern era	»	309
4. Details of the classical evolution	»	310
5. Quantum corrections	»	315
5·1. Overwiew	»	315
5·2. Scalar perturbations	»	318
5·2.1. Exact solution for power law inflation	»	321
5·2.2. Slow-roll expansion for general potentials	»	323
5·3. Tensor perturbations	»	324

A. MASIERO – Mixed dark matter and supersymmetry.

1. Introduction	»	331
2. Lepton number violation and neutrinos as HDM candidates	»	333
3. The lightest supersymmetric particle (LSP)	»	334
4. Lepton number violation in SUSY	»	337
5. Mixed DM	»	339

K. GRIEST – The nature of the dark matter.

1. Introduction	»	343
2. Physical evidence for dark matter	»	343
2·1. Spiral galaxies	»	344
2·2. Clusters of galaxies	»	345
2·3. Large-scale flows	»	346
2·4. The baryonic content of the Universe	»	347
2·5. Distribution of dark matter in the Milky Way	»	347
3. Brief survey of dark-matter candidates	»	348
4. Thermal relics as dark matter (WIMPs)	»	349
5. Nonthermal relics as dark matter (axions)	»	350
6. Search for WIMP dark matter (neutralinos)	»	352
6·1. Motivation for supersymmetry	»	352
6·2. Relic abundance in more detail	»	355
6·3. Accelerator constraints	»	356
6·4. Detection techniques	»	359

6'5. Direct detection ... pag. 359
6'6. Indirect detection ... » 362
7. Baryonic dark matter (MACHOs) ... » 365
7'1. Microlensing ... » 365
7'2. The MACHO Collaboration experiment ... » 367
7'3. Event selection ... » 367
7'4. Detection efficiency ... » 370
7'5. Interpretation of LMC events ... » 371
7'6. Interpretation of bulge events ... » 373
7'7. Advantages of having many events ... » 374
7'8. MACHO conclusion ... » 375
8. Conclusions ... » 375

M. TEGMARK – Doppler peaks an all that : CMB anisotropies and what they can tell us.

1. Introduction ... » 379
2. Sources of CMB fluctuations: an overview ... » 380
2'1. Primary fluctuations ... » 380
2'2. Secondary fluctuations ... » 382
2'2.1. Gravitational effects ... » 382
2'2.2. Effects of local reionization ... » 385
2'2.3. Effects of global reionization ... » 386
2'3. «Tertiary» fluctuations (foregrounds and headaches) ... » 388
2'4. Extragalactic point sources ... » 390
2'4.1. Radio sources ... » 390
2'4.2. Infrared sources ... » 391
2'5. Diffuse galactic sources ... » 391
2'5.1. Power spectrum ... » 391
2'5.2. Frequency dependence ... » 392
2'6. Local sources ... » 392
3. The origin of primary anisotropies ... » 393
3'1. Before recombination: acoustic oscillations ... » 394
3'1.1. The classical Jeans analysis ... » 394
3'1.2. The relativistic multifluid case ... » 395
3'1.3. A toy model ... » 396
3'1.4. The random element ... » 397
3'1.5. The Doppler peaks vanish ... ... » 398
3'1.6. ... and return ... » 398
3'1.7. The WKB approximation ... » 400
3'2. During recombination: damping and diffusion ... » 401
3'3. After recombination: curvature and projection effects ... » 401
3'4. Parameter dependence ... » 402
4. How accurately can the CMB pin down cosmological parameters? ... » 404
4'1. The parameter estimation problem ... » 404
4'2. The error bars ... » 405
4'3. A geometric interpretation ... » 406
4'4. Real-world complications: foregrounds and incomplete sky coverage ... » 407
4'4.1. Foregrounds ... » 407
4'4.2. Incomplete sky coverage ... » 409

5. Summary .... pag. 410
Appendix A – Cosmic statistics—a primer .... » 411
A˙1. Random fields .... » 411
A˙1.1. Ergodicity .... » 411
A˙1.2. Gaussianity .... » 411
A˙2. The 3D power spectrum .... » 412
A˙3. Working with spherical harmonics .... » 413
A˙4. Random fields on the sphere .... » 414

DARK MATTER MODELS AND LSS

A. KLYPIN – Numerical simulations in cosmology. - I.

1. Introduction .... » 419
2. Equations of evolution of fluctuations in an expanding universe .... » 421
3. Methods .... » 423
4. Distribution of the matter and effects of resolution .... » 424
5. Halo identification and overmerging problem .... » 430

A. KLYPIN, J. R. PRIMACK and J. HOLTZMAN – Numerical simulations in cosmology.

II. - Small-scale power spectrum and correlations in ΛCDM model.

1. Introduction .... » 435
2. Model .... » 437
3. Simulations .... » 438
4. Results .... » 438
4˙1. Power spectrum .... » 438
4˙2. Correlation function .... » 441
5. Discussion, and alternative ΛCDM models .... » 446

A. KLYPIN, G. YEPES, R. KATES and A. KHOKHLOV – Numerical simulations in cosmology.

III. - Hydrodynamics, cooling and supernovae feedback.

1. Introduction .... » 451
2. Physical assumptions and motivations .... » 452
2˙1. Multiphase medium .... » 452
2˙2. Cooling of the hot gas .... » 453
2˙3. Transfer of gas to the «cold» phase .... » 453
2˙4. Star formation .... » 454
2˙5. Effects of supernovae .... » 455
2˙6. Hydrodynamical equations .... » 456
2˙7. Solution of the hydrodynamical equations .... » 457
3. Cosmological model .... » 457
4. Stellar-population synthesis .... » 458
5. Results .... » 459
6. Conclusions .... » 465

S. GOTTLÖBER – Broken scale-invariant spectra of cosmological perturbations.

1. Introduction ... pag. 467
2. Generation of perturbations and BSI spectra ... » 469
3. Observational constraints on BSI spectra ... » 473
4. Conclusion ... » 476

M. STEINMETZ – Simulating galaxy formation.

1. Introduction ... » 479
2. N-body simulations ... » 480
   2·1. Numerical methods to solve the N-body system ... » 481
   2·2. The special-purpose hardware GRAPE ... » 482
3. Hydrodynamics ... » 484
   3·1. The hydrodynamical equations ... » 484
   3·2. Smoothed-particle hydrodynamics ... » 485
   3·3. Shock waves ... » 487
   3·4. Variable smoothing length ... » 490
   3·5. Time stepping ... » 492
4. Cooling and heating processes ... » 493
   4·1. Radiative cooling and photoionization ... » 494
   4·2. Star formation and feedback processes ... » 496
5. Numerical simulations of galaxy formation ... » 498
   5·1. An analytic galaxy formation model ... » 498
   5·2. Results of numerical simulations ... » 499

S. BONOMETTO – On the nature of the volatile component of dark matter from large-scale structure measurements.

1. Introduction ... » 509
2. Mixed-dark-matter parameters ... » 510
3. Models for hot and cold decoupling ... » 512
   3·1. Hot decoupling ... » 512
   3·2. Cold decoupling ... » 514
4. The void probability function as a model discriminator ... » 515
5. Transfer function for V + C DM models ... » 519
6. Conclusions ... » 523

L. MOSCARDINI – Testing dark-matter models by the cluster velocity field.

1. Introduction ... » 527
2. The simulations ... » 528
   2·1. The Zel'dovich approach ... » 528
   2·2. Comparison with N-body velocities ... » 529
3. The power spectrum models ... » 531
4. The bulk flow velocity ... » 533
5. The cumulative probability velocity function and the velocity dispersion ... » 535

NONLINEAR DYNAMICS OF DENSITY FLUCTUATIONS

T. BUCHERT – Lagrangian perturbation approach to the formation of large-scale structure.

1. Lagrangian theory of self-gravitating flows .... pag. 543
2. Lagrangian dynamics of Eulerian fields .... » 549
3. Lagrangian perturbation theory .... » 552
   3'1. The Lagrangian perturbation approach .... » 552
   3'2. A comment on average flows .... » 553
   3'3. Perturbations solutions at first order .... » 555
   3'4. Higher-order solutions .... » 558
   3'5. Comparison of Eulerian and Lagrangian perturbation theory .... » 559
   3'6. Limitations of the Lagrangian perturbation theory .... » 560

F. R. BOUCHET – Introductory overview of Eulerian and Lagrangian perturbation theories.

1. The fluid equations .... » 565
   1'1. Microscopic description .... » 566
   1'2. Macroscopic description .... » 566
   1'3. Velocity moments and the fluid limit .... » 567
2. Eulerian perturbative solutions .... » 569
   2'1. Linear density field .... » 569
      2'1.1. Dust universe, $p = 0$ .... » 569
      2'1.2. Jeans length of an ideal fluid with $p = p(\varrho)$ .... » 570
   2'2. Linear peculiar-velocity field .... » 571
      2'2.1. Solution in a dust universe .... » 571
      2'2.2. Application to data .... » 571
   2'3. Nonlinear corrections .... » 572
3. Some basic applications .... » 573
   3'1. The PDF as a measure of large-scale structures .... » 573
   3'2. Moments of the PDF .... » 574
      3'2.1. Skewness of the unsmoothed density field .... » 574
      3'2.2. Smoothing the density field .... » 575
      3'2.3. Skewness of the velocity field PDF .... » 576
      3'2.4. Kurtosis .... » 578
   3'3. Edgeworth expansion of the PDF .... » 578
   3'4. Validity of perturbation theory .... » 580
4. Further developments .... » 581
   4'1. Higher-order moments .... » 581
   4'2. Higher-order corrections to the moments .... » 582
   4'3. General initial conditions .... » 582
   4'4. Biasing and comparisons to data .... » 584
5. Zel'dovich approximation .... » 585
   5'1. Derivation from Eulerian theory .... » 586
   5'2. Galactic-spin origin .... » 586
   5'3. Density contrast and pancakes .... » 587
6. Lagrangian perturbation theory .... » 588
   6'1. Perturbative equations .... » 589

6˙2. Low-order solutions .... pag. 591
6˙2.1. First order .... » 591
6˙2.2. Second order .... » 592
7. Applications .... » 592
7˙1. Moments in the Lagrangian approach .... » 593
7˙2. Redshift space skewness .... » 594
7˙3. Approach of the nonlinear regime. .... » 596
8. Conclusions .... » 597

S. MATARRESE – Relativistic cosmology: from superhorizon to small scales.

1. Introduction .... » 601
2. Relativistic dynamics of collisionless matter .... » 605
3. Newtonian approximation .... » 611
4. Beyond the Newtonian approximation .... » 618
5. Fluid-flow approach .... » 621
6. Conclusions .... » 625

P. COLES – Models of nonlinear clustering.
II. - Applications of the truncated Zel'dovich approximation.

1. Introduction .... » 629
2. The Zel'dovich approximation and beyond .... » 630
3. Cluster simulations using the TZA .... » 632
3˙1. Large-scale structure and galaxy clusters .... » 633
3˙2. The simulation method .... » 634
4. The spatial clustering of clusters .... » 637
5. The cluster dipole and the value of Ω .... » 638
6. Conclusions .... » 642

S. N. GURBATOV – The adhesion approximation in the description of the large-scale structure of the Universe.

1. Introduction .... » 645
2. Basic cosmological equations .... » 646
3. The Zel'dovich and adhesion approximations .... » 648
4. Burgers equation and cellular structure .... » 651
5. A new approach to the adhesion approximation .... » 654
6. Burgers equation and potential turbulence .... » 658

BERNARD J. T. JONES – A «simple» dynamical model for the origin of the large-scale structure in the Universe.

1. Introduction .... » 661
1˙1. Simulating universes .... » 661
1˙2. Understanding what we see .... » 661
1˙3. Analytic approaches .... » 662
1˙4. Quantifying structure .... » 662
1˙5. Organization of lecture .... » 663

2. A classical dynamics Tripos question .... pag. 663
2·1. Comments on the examination question .... » 664
2·2. Cosmology .... » 665
3. Elementary stachastic dynamics .... » 666
3·1. Particle in a time-varying field: I. .... » 666
3·2. Particle in a time-varying field: II. .... » 667
4. The diffusion equation .... » 667
4·1. The «classical» diffusion equation .... » 667
4·2. The random heat equation .... » 668
5. The path integral: some insights .... » 669
5·1. The maximum of the potential .... » 669
5·2. Choosing R and l .... » 670
5·3. A small problem—cosmic variance .... » 670
6. From path integrals to reality .... » 671
6·1. A useful result in statistics .... » 671
6·2. Moments of the solution of the RH equation .... » 672
6·3. Intermittency and the RH equation .... » 672
7. What has this to do with cosmology? .... » 673
7·1. Some cosmology .... » 673
7·2. Equation of motion .... » 673
8. What does this do for us? .... » 675

A. PROVENZALE and G. MURANTE – Scaling behaviour in gravitational clustering.

1. Introduction .... » 677
2. Quantifying the scaling behaviour .... » 679
3. Evolution of CDM initial conditions .... » 680
4. Stability of the scaling behaviour .... » 682
5. Dependence on initial conditions .... » 686
6. Summary and conclusions .... » 688

S. BONOMETTO – Frontiers of cosmology.

1. Introduction .... » 691
2. Generic consequences and suitable tunings in inflationary theories .... » 693
3. An effective cosmological constant from the inflationary paradigm .... » 695
4. Tuning inflation and the cultural boundary .... » 699

Elenco dei partecipanti .... » 703