Syllabus and Instruction Plans for JAP Courses: Jan.-April Semester

JAP syllabus Committee

November 29, 2012

1 Stellar & High Energy Astrophysics: AA 370 3:0 (45 hours)

Optional topics are given in *italics*. Some of these may have been cursorily covered in FoA or not at all and the instructor may decide the depth of the coverage required accordingly.

1.1 Stellar Structure and Evolution (15 hours)

1. **Structure**:

   (a) Fundamentals: Basic assumptions, Integral theorems from hydrostatic equilibrium, Homology transformations, Polytropes

   (b) Sources and Sinks of Energy: *Energies of stars, Time scales, Generation of Nuclear Energy*

   (c) Energy Flow: *Ionization, Abundances, and Opacity of Stellar Material, Radiative Transport and temperature gradients*, Convective, and Conductive energy transport, Convective Stability, Equations of Stellar Structure, Construction of a Model Stellar Interior

   See Chapter 2 to 4 in [1].

2. **Nucleosynthesis**:

   (a) Thermo-nuclear Reaction Rates: *Kinematics & Energetics, Cross-sections & reaction rates, Non-resonant reaction rates*, Nuclear states, Penetration factors, maximum cross-section and resonant reaction, Resonant reaction rates in stars, electron shielding

   (b) Major Nuclear Burning Stages in Stellar Evolution: *PP reaction, PPI Chain, PPII & PPIII Chain*, CNO Bicycles, Helium Burning, Advanced burning stages, Photodisintegration

   (c) Synthesis of Heavy Elements: *Photoionization rearrangement & Silicon burning*, Nuclear statistical equilibrium and the e-process, Nucleosynthesis of heavy elements by n-capture

   See Chapter 4 to 7 in [2].

3. **Evolution**:

   (a) Simple Stellar Models: Polytropic Gaseous Spheres, Homologous contraction, Zero-age main sequence, other main sequences, Hayashi Line, Stability Consideration

   (b) Early Stellar Evolution: *Onset of Star Formation, Formation of Proto-stars*, Pre-main sequence contraction, Initial to the present Sun, Evolution on the Main sequence

   (c) Post Main sequence Evolution: Evolution through Helium burning for low-mass, intermediate mass, and massive stars

   (d) Late phases of Stellar Evolution: Evolution of the AGB stars, late phases of core evolution, qualitative overview of final explosion and collapse.

   See Chapters 4 to 7 in [3].

1.2 Compact Object and High Energy Astrophysics

1. **Isolated Compact Object Physics (12 hours)**

   (a) Core-collapse Supernova: hydrodynamics, shock waves, neutrinos, explosion in ISM, collapsar

   (b) White dwarf: observed properties, EOS, structure, formation and cooling.

   (c) Neutron star: structure, EOS, mass limit, cooling, surface emission; Pulsars: phenomenology, magnetosphere physics, Period evolution, interior dynamics.

   (d) Black holes: *Introduction to GR, Schwarzschild and Kerr metric*, motion of test mass, photon propagation, Penrose process

   See [30] for (a); [5] & [6] for (b)-(d).

2. **Accretion Physics (8 hours)**

   (a) Accretion in binary systems: *Roche lobe overflow, disk formation*, wind accretion, effect on binary evolution

   (b) Spherical Accretion: Bondi and Bondi-Hoyle, feeding of supermassive BHs

   (c) Accretion physics: The origin of viscosity (MRI), time-scales and stability, thin and thick disks, radiatively inefficient accretion, disk dynamics, precession and warp.

   (d) Accretion onto Neutron Stars: X-ray pulsars, bursts, QPOs; pulsar recycling

   (e) White dwarf accretion: CVs, Nova and Type Ia SN, AIC vs explosion, ultra compact binaries

   (f) Supermassive BHs: Introduction to AGN, radio sources, quasars, synchrotron radiation, minimum energy, supermassive binary BHs

   (g) Jets: relativisitic effects, radiation from, launching and collimation mechanisms, Blandford-Znajek.

   See [7] & [8] (a-e); [9] & [10] (f-g).

3. **High Energy Astrophysics (10 hours)**

   (a) Photon interaction with matter: *detection of high energy radiation (X-ray and Gamma ray)*

   (b) Gamma Ray Bursts: Simple fireball models, afterglows, relativistic shocks, SWIFT results, GLAST/Fermi, Magnetars

   (c) Gravitational wave sources: NS/NS and NS/BH binaries, rotating collapse, LIGO and LISA sources

   (d) Cosmic rays: EeV cosmic ray puzzles, particle acceleration, extremely high energy neutrinos

   (e) High-energy astrophysics of cluster of galaxies: Mechanical/radiative feedback of supermassive black hole in cluster

   See [11] for (a); [7] for (b); [12] for (c) and (d); [13] for (d); [10] & [9] for (e).

2 Galaxies and the interstellar medium: AA 365 3:0 (45 hours)

1. **Galaxies, an overview (1 hour)** Cover essentials of Chapter 1 of [14]. Include evidence for a massive black hole at the Galactic center, from stellar positions, radial velocities, proper motions.

2. **Astronomical measurements (4 hours)** Positions, motions and coordinate systems ([14] 2.1); Distance determination from velocities ([14] 2.2); Magnitudes and Colours ([14] 2.3); Stellar luminosity function ([14] 3.6); Interstellar dust ([14] 3.7)

3. **Stellar systems I (5 hours)** Introduction (3 hr; [15] 1.2, 2.2, 3.1, 3.1.1, 4.1); Spherical systems (1 hr; [15] 4.3); Jeans equations (1 hr; [15] 4.8). *Optional reading: Appendix F of [15] on fluid mechanics*

4. **Observations of galaxies (5 hours)** Galaxy morphology ([14] 4.1); The Local Group ([14] 4.1.4, [15] Box 3.1); Galaxy photometry ([14] 4.2, 4.3);

5. **Stellar systems II (7 hours)** Potential theory for flattened systems (1 hr; [15] 2.3); Orbits in axisymmetric galaxies (1 hr; [15] 3.2). Dynamics of the solar neighborhood (1 hr; [14] 10.3; [15] 4.4.3); Disc dynamics and spiral structure (2 hr; 6.1, 6.2); Mergers and dynamical friction (1 hr; [15] 8.1, 8.5; [14] 4.6.1); Globular clusters (1 hr; [15] 7.1; [14] 4.5).

6. **Interstellar media of galaxies (2 hours)** Introduction ([14] 8.1, 8.2; [16] 1, 2); Rotation of the Milky Way ([14] 9.1, 9.2); a useful reference is [17].

7. **Microscopic processes in the ISM (4 hours; [16] 3, 4)** Cooling by ions, atoms and molecules (1 hr); Heating by starlight, cosmic-rays and X-rays (1 hr); Molecule formation; ion-atom-molecule reactions (1 hr); Grains (1 hr).

8. **Radiatively excited regions (2 hours; [16] 5)** Ionization, recombination and the structure of HII regions; Forbidden lines; Radio-frequency spectra of nebulae. *Optional reading: [16] ch.6 'Introduction to gas dynamics'*

9. **Supernovae and massive stars (3 hours; [16] 7.3–7.5)** Supernova explosions and supernova remnants; Consequences of supernova explosions for the ISM; Effects of groups of massive stars

10. **Star formation (1 hour, [16] 8.1)**

11. **Galactic chemical evolution (1 hour; [14] 5.3, 5.4)**

12. **Active Galactic Nuclei (5 hours)** Observational properties and types of AGNs ([10] 1); The black hole paradigm ([10] 4); Radio emission–'radio galaxies' ([10] 9); Optical and high energy emission ([10] 8, 10); Unification scheme ([10] 12)

13. **Clusters of Galaxies (2 hours, [18] 4.1-4.3)** Dynamics and mass estimate; morphology–density relation; Intracluster gas, Cooling flow, Sunyaev-Zeldovich effect

14. **The intergalactic medium (1 hour; [18] 19)** Absorption systems; the Gunn–Peterson effect

15. **Formation and evolution of galaxies (2 hours)** Observational constraints: Lyman break galaxies; red/blue sequence ([19] 2, 3); importance of cooling; origin of angular momentum ([18] 20)

3 General Relativity & Cosmology: AA 372 2:0 (30 hours)

1. **Review of Special Relativity (SR; 2 hours)** Invariance of interval, Lorentz transformations; four vectors; equations of motion; energy and momentum in SR; stress-energy tensor in SR. ([20]: chapter 2 § 1–8, 10; [21]: chapters 1–4)

2. **General Theory of Relativity (6 hours)** Equivalence principle; freely falling observers as inertial observers; need for arbitrary coordinate transformations for description of physics in an arbitrary gravitational field; introduction to metric; general covariance and the notion of contravariant and covariant vectors; equations of motion; geodesic equation for massive particles, Christoffel symbols. ([20]: chapter 3, § 1–4, § 1–9; [21]: chapters 5–7)

3. **Applications of the Schwarzschild metric (4 hours)** Gravitational redshift; effective potential, particle orbits; precession of orbits, case of mercury; geodesic equation for massless particles: bending of light. ([20]: chapter 3, § 5, chapter 8, § 1–7; [22]: chapter 14)

4. **Curvature of space-time (3 hours)** Energy-momentum tensor and Einstein equations; weak field limit of gravity; gravitational waves; Hulse-Taylor pulsar as a test of GR. ([20]: chapter 6, § 1–5, chapter 7: § 1–2, chapter 10: § 1–3; [22]: chapter 21; [21]: chapter 9)

5. **Background Cosmology (3 hours)** Hubble's law; homogeneous and isotropic universe; Newtonian cosmology; generalization to the FRW metric. ([20]: chapter 14, § 1–6)

6. **The FRW universe (3 hours)** Einstein's equations; average density of the universe; notion of critical density deciding the geometry of the universe; contents of the universe; need for dark matter; cosmological redshift; look back time; age of the universe; distance measures in an expanding background; observational evidence (observations of SN Ia); accelerating universe; dark energy. ([20]: chapter 15, § 1–3, research papers)

7. **Thermal history of the universe I (3 hours)** Phase space distribution function; thermodynamics in early universe; origin of dark matter; neutrinos as dark matter. ([23]: chapter 3,5)

8. **Thermal history of the universe II (2+1+1 hours)** Nucleosynthesis in the early universe; cosmic background radiation and the epoch of recombination; inflationary universe. ([23]: chapter 4, 8; [20]; [24])

9. **Structure formation in the universe (2 hours)** Newtonian perturbation theory, Zeldovich approximation, spherical top-hat collapse. ([25], chapter 2; [24])

4 Numerical and Statistical Techniques: AA 372 2:0 (30 hours)

Since this is a hands-on course, there should be plenty of homework assignments that involve writing programs.

1. **Errors, Stability, Convergence, Interpolation (3 hours)** Integer, floating-point representation, machine precision; round-off error. Truncation Error: Taylor expansion, order of accuracy. Numerical Stability: CFL condition, von-Neumann stability analysis. Fundamental theorem: consistency+stability $\iff$ convergence. Interpolation: polynomial, rational, cubic splines. Chapters 1.3, 19.1, 3.0-3.3, 2.4 in [26], Chapter 8 in [27]; [32].

2. **Numerical Root Finding & Numerical Integration (3 hours)** Root finding: single variable: bracketing; bisection, secant methods; Newton-Raphson, convergence rate. multi-D Newton-Raphson. **Numerical Integration:** mid-point rule, quadrature; Richardson/Romberg extrapolation; Monte Carlo integration for multi-D integrals. Chapters 9.0-9.2, 9.4, 9.6, 4.0-4.4, 7.6 in [26]; [32].

3. **Linear Systems and Matrices (2 hours)** Computational expense of matrix operations; Gauss-Jordan elimination; pivoting; Gaussian elimination; L-U decomposition; banded matrices; LAPACK.[1] Chapters 2.0-2.5 in [26]; [28]; [32].

4. **Ordinary Differential Equations (ODEs; 3.5 hours)** Reduction to first order; initial/boundary value problems; IVPs: forward/backward Euler; Runge-Kutta: RK2, RK4; Leap-frog: symplectic; adaptive step-size; stiff equations: implicit method. Two-point BVPs: shooting method; relaxation methods. Chapters 16.0-16.6, 17.0-17.3 in [26]; [32].

5. **Partial Differential Equations (PDEs; (3.5 hours)** IVPs (marching in time) vs BVPs (relaxation; Ax=b). Conservative PDEs: advection, diffusion, Euler equations. Lax method; space-time diagrams; upwinding; artificial viscosity. Diffusion equation: explicit, implicit, Crank-Nicolson methods. multi-D IVPs: operator splitting. Relaxation methods for BVPs: Jacobi, Gauss-Seidel. Chapters 19.0-19.6 in [26]; Chapters 4, 6 in [27]; [32].

6. **Estimation theory, data modeling and presentation of data (9 hours)** Basic probability theory: random processes of single variable; continuous and discrete distributions, notion of statistical ensemble; ensemble average; mean, median and mode; Cumulative Probability Distribution Function (CPDF); Poisson, Gaussian and exponential distributions; random vs. systematic noise; direct estimation of simple physical quantities (such as length and time), difference between accuracy and precision; Multivariate random processes, joint probability distribution; conditional probability; statistical independence; propagation of errors for a sum of random variables, moment generating function, properties of Gaussian distribution. Standard error for an arbitrary function of random variables in the limit of small noise. *Estimation Theory*: Maximum Likelihood (ML) estimation, χ^2 method as the ML estimate for a Gaussian process; Fisher and covariance matrix; Cramér-Rao inequality and the significance of Fisher matrix; graphical presentation of estimated parameters; Bayesian method of parameter estimation; model selection. Discovering new physics using correlation between astrophysical quantities; cross correlation function; linear regression; significance of correlation; rank correlation test. Monte-Carlo simulation of data; random number generation: using CPDF to generate random numbers from a uniform distribution; design of experiments. Refs.: [30]; [31]; [33]; [34].

7. **Application of Fourier technique to random fields (6 hours)** Random fields in space/time such as: scalar matter over-density $\delta\rho/\rho$, angular CMB temperature fluctuations $\Delta T/T$ and

[1] Web resource: `http://www.netlib.org/lapack/`

temporal light curves of astrophysical objects; vector turbulent velocity field $\vec{v}_{\rm turb}$; time/space average vs ensemble average and the ergodic hypothesis; working with random fields through discretization; two point correlation function and its significance for Gaussian fields. *Fourier transforms*: continuous and discrete; power spectrum of continuous and discrete data; Weiner-Kinchin theorem; convolution theorem and the central limit theorem; sampling of data; aliasing; bandwidth and information content; Nyquist criteria; filtering; impulse-response/point-spread function; side-lobes & window functions; Matched filtering and optimum detection/estimation; Ref.: [29], [35].

References

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