Proposed Syllabus and Instruction Plans for JAP Courses: Aug.-Dec. Semester

JAP syllabus Committee

June 22, 2012

1 Fundamentals of Astrophysics: PH 217 (AUG) 3:0 (45 hours)

Optional topics are given in *italics*.

1.1 Introduction, Distances & Measurement systems (6 hours)

Celestial phenomena, its connection with established and new physics; typical physical scales/conditions in astrophysics; order of magnitude estimation; astronomical observations: electromagnetic, look back time; *cosmic rays, gravitational radiation*, earth vs space based observations, role of atmospheric transmission; celestial sphere, the ecliptic, RA/DEC coordinates, Galactic coordinates; luminosity/flux, magnitude scale, absolute/apparent magnitude; *electromagnetic wavebands*, spectroscopy; the third dimension: distance measurement, A.U., parsec; standard candles, distance ladder; stellar kinematics: proper motion, line of sight velocity; stellar mass measurement; visual, astrometric, eclipsing, spectroscopic binaries; distances to open clusters; extrasolar planets with radial velocity, detection techniques (e.g., transit, microlensing, direct imaging, timing).

See Chapter 1 in [1]; Chapters 1, 2 in [5]; Chapter 1 in [3]; Section 27.1 in [2]

`Web resources: Astronomy Picture of the Day, arXiv`

1.2 Telescopes, Radiation & Sun as a star (6 hours)

Telescopes: radio, infrared, optical, X-ray, gamma ray; collecting area, diffraction limit, atmospheric seeing; *adaptive optics, speckle imaging, aperture synthesis, spectroscopy (prisms and gratings), polarimetry, imaging, photometry.* **Fundamentals of radiation**: geometric optics, specific intensity, energy density, radiative transfer equation, extinction and emission of light; opacity, optically thick/thin media, black body distribution, *local thermal equilibrium between matter and radiation and its connection with black body radiation, Rayleigh-Jeans limit and radiative transfer in terms of temperature.* **Sun as a star (qualitative)**: Solar spectrum, effective temperature, $T_{\rm eff}$, luminosity; photospheric absorption lines; limb darkening; energy source: Kelvin time scale, nuclear fusion; energy transport in the sun: light propagation in terms of photons, Thomson scattering, mean free path, photon diffusion (random walk) inside the Sun; convective instability; structure: core, radiative zone, convective zone, photosphere; chromosphere, transition region, corona; *X-ray emission, magnetic fields, butterfly diagram.*

See Chapters 2, 5 in [3]; Chapter 6 in [2]; Chapters 1, 2 in [5]; Chapter 2, Section 4.8 in [1].

1.3 Stellar Structure (8 hours)

Stellar models: hydrostatic equilibrium, gas/radiation pressure; order of magnitude estimates, theoretical main sequence; opacity: Thomson, *Kramer's, scattering, role of* H^- opacity in sun, energy balance; **nuclear energy production in stars**: binding energy per nucleon, efficiency of fusion, *calculation of nuclear reaction rates*, tunneling in Coulomb barrier, *Gamow's calculation.* important nuclear reactions in stars: pp chain, *neutrino production in the sun & consequences; neutrino oscillations*, CNO cycle, triple alpha reaction, *rate limiting reactions*; nuclear resonances; *constitutive relations and detailed stellar structure*, opacity and onset of convective instability; **observed stellar properties**: main sequence, luminosity dependence on mass, stellar classification based on spectra, connection with Saha ionization formula; HR diagram; star clusters & distance determination.

See Chapter 2 [5]; Chapter 8, Sections 10.3, 10.5 in [2]; Chapters 6, 9 in [3]; Chapter 3, 4 in [1].

1.4 Stellar evolution and accretion physics (8 hours)

Core He burning, shell burning; red giant phase; stellar winds: Parker's model for solar wind, planetary nebulae; white dwarf physics, electron degeneracy pressure, Chandrasekhar mass limit; **Evolution in binary systems**: effective potential in rotating frame, Lagrange points; Roche lobe, mass overflow; type Ia supernovae; type II supernova, neutronization; formation of elements heavier than iron; neutron drip, Neutron Stars (NS); NS observed as pulsars: pulsar magnetospheres, $\dot{P}$ from oscillating magnetic dipole formula, black holes formation for $M > N_S$; qualitative discussion of horizon, Hawking radiation; phenomenology and observations of GRBs and connection with supernovae. **Accretion Physics**: energy efficiency; X-ray binaries vs. supermassive BHs (AGN); thin disk model for optically thick accretion flows; need for turbulent viscosity; magnetorotational instability; derivation of multicolor blackbody spectrum; *opacity sources; observations.*

See Chapters 4, 5 in [1]; Chapters 2, 4 in [5]; Chapter 6, 7, 10 in [3].

1.5 Galaxy and Extragalactic Astronomy (8 hours)

Types of galaxies: spirals, ellipticals and irregulars, Hubble pitchfork classification. **Milkyway components**: gas, stars, magnetic field and cosmic rays; satellites; 21 cm line, rotation curve, dark matter; Jeans instability and star formation, HII regions; phases and components of interstellar medium; cosmic rays. **Galactic dynamics**: orbits in axisymmetric potentials, epicyclic limit; Oort's A & B constants, local differential rotation, collisionless Boltzmann equation, Jean's equations, DFs, $f(E)$, isothermal models gas in galaxies. **Evolution of Galaxies**: starbursts, galaxy formation models; color-magnitude diagram for galaxies; initial mass function; **Active Galaxies**: observations of active galaxies and quasars, unified model, radio lobes and jets; relativistic apparent superluminal motion, Doppler boosting, blazars; properties of accretion flows around supermassive black holes; M-σ relation for central black holes; Sgr A*, the Galactic center black hole. Extragalactic distance scale, classification of clusters, the local group, superclusters, hot intercluster gas, mass estimates from virial theorem applied to galaxies and hydrostatic equilibrium of hot gas; structure on largest scales.

See Chapters 5, 6 in [5]; Chapters 6, 7, 9 in [1]; Chapter 25, 27, 28 in [2]; Chapter 7, 9 [6].

1.6 General Relativity, Cosmology and Structure Formation (9 hours)

Olber's paradox; difficulty with Newtonian cosmology; brief introduction to general theory of relativity, especially the line element; Schwarzschild metric, *horizon, orbits, Hawking radiation*; FRW metric as a consequence of cosmological principle; redshift, angular and luminosity distances; evolution of scale factor from Newtonian cosmology; density parameter; LCDM cosmology; flatness and horizon problems, basics of inflation theory; thermal history of the Universe, *big bang nucleosynthesis*; microwave background. **Structure formation**: Jeans instability in an expanding background; initial perturbation and anisotropies in CMBR, formation of dark matter halos, galaxy formation and star formation; *millennium simulation; Sunyaev-Zeldovich effect; neutral hydrogen and other elements in the IGM, Lyman α forest and damped clouds; reionization, AGN/star-formation history of the universe; Gunn-Peterson effect.*

See Chapters 11, 12 in [4]; Chapters 6, 7 in [6]; Chapters 10, 11, 14 in [1].

2 Fluid Mechanics and Plasma Physics, AA 363 (AUG) 2:0 (30 hours)

2.1 Introduction to fluids (3 hours)

Fluids as continuous medium with length and times scales > mean free path and collision times. Local thermal equilibrium, pressure $p = p(\rho, s)$; e.g. perfect gas equation of state. Flow and velocity field, convective derivative. Equations of fluid dynamics (mass, momentum and entropy) for ideal fluids. Condition on equation of state for hydrostatic equilibrium.
Worked examples: Hydrostatic equilibrium of plane-parallel atmosphere; isothermal atmosphere and scale length. Convective instability and Schwarzschild's criterion.

2.2 Elementary properties of flows (5 hours)

Equations of fluid dynamics in conservation form, conserved flux densities in steady flow. Streamlines and Bernoulli's equation with applications (e.g. lift on a 2-dimensional aerofoil; small-Mach no. condition for flow to be nearly incompressible). Vorticity, Kelvin's circulation theorem, vorticity conservation in 2-dim flows, vortex stretching in 3-dim flows. Rotating fluids: Coriolis force, geostrophic flows.
Worked/Home examples: Solar Wind and Bondi accretion/Accretion disc, von Ziepel's theorem, Taylor-Proudman theorem.

2.3 Linear Waves and Instability (3 hours)

Sound waves: wave equation, dispersion relation and general solution of initial value problem. Gravity waves: consider one fluid on top of another with both fluids moving with different horizontal speeds in the same direction; derive the dispersion relation; discuss internal and surface gravity waves, Rayleigh-Taylor & Kelvin-Helmholtz instabilities (see section 1.4 of Drazin & Reid)
Home work: Inertial waves in a steadily rotating flow.

2.4 Navier-Stokes equation (3 hours)

Non ideal fluids: discuss at elementary kinetic theory level the origins of dissipation and transport, viscosity as energy dissipation and momentum transport. Motivate derivation of Navier-Stokes equation. Derive equation for viscous energy conservation and entropy production. Order-of-magnitude discussion of boundary layers. Scaling in the NS equations: Reynolds number, order-of-magnitude discussion of Stokes flow past a sphere at low Re, transition to turbulence, phenomenological treatment of Kolmogorov cascade.
Home work: Stokes flow past a sphere at low Re.

2.5 Supersonic flow (4 hours)

De-laval nozzle, shock formation, shock thickness and viscosity, Rankine-Hugoniot jump conditions. Brief discussion of cooling and cooling length, isothermal shocks. Order-of-magnitude discussion of Sedov-Taylor blast wave. Application to supernova shocks, discussion of adiabatic and momentum conserving phases of evolution.
Home work: Riemann invariants in 1-dim flows. Full solution of Sedov-Taylor.

2.6 Convection (2 hours)

Thermal diffusivity and its effect on the entropy equation. Conductive and convective transport of heat equation. Mixing length theory and transport of heat, application to plane-parallel atmospheres

and stars.
Home work: Rayleigh-Benard convection.

2.7 Introduction to Plasmas (3 hours)

Particle orbit theory and adiabatic invariants. 2-component plasmas. Debye shielding and length in a plasma in thermal equilibrium. Cold plasma oscillations.

2.8 Magnetohydrodynamics (5 hours)

Derivation of induction equation, magnetic diffusion, flux freezing. Lorentz force and momentum equation. Alfven, fast and slow waves. Elements of dynamo theory.
Worked examples: Parker spiral, Pulsar magnetospheres, Magnetorotational instability.

2.9 Collisionless plasmas (2 hours)

Coulomb collision times. 6-dim phase space, distribution functions. Vlasov equation. Landau damping.
Worked example: Connections with stellar systems.

Recommended references: [7], [9], [10], [8] and [11].

3 Radiative Processes in Astrophysics, AA 362 (AUG) 2:0 (30 hours)

The lecture plan for 30 hours will mostly follow the book, *Radiative Processes in Astrophysics* by Rybicki & Lightman [12].

1. Radiative Transfer (5 hours)

   Chapter 1, except for section 1.7 on scattering.

2. Radiation Fields (2 hours)

   Chapter 2.

3. Radiation from moving charges (3 hours)

   Chapter 3.

4. Special Relativity (4 hours)

   Chapter 4. Can drop sections 4.3 and 4.4. Equation 4.65 (which occurs near the end of section 4.4), however is needed because it gives Lorentz transformations of E & B fields. I think these transformations are more simply derived after the 4-force is introduced a bit later in section 4.7.

5. Bremsstrahlung (1 hour)

   Chapter 5. Can give section 5.4 on relativistic bremsstrahlung as home work.

6. Synchrotron Radiation (3 hours)

   Chapter 6. Can go over section 6.4 on spectrum and polarization details quickly in class using slides and give the derivation as home work.

7. Compton Scattering (2 hours)

   Chapters 7, sections 7.1, 7.2, 7.4, 7.5 only. Can assign parts of uncovered sections as home work.

8. Plasma Effects (2 hours)

   Chapter 8.

9. Atomic Structure (3 hours)

   Chapter 9.

10. Radiative Transitions (3 hours)

    Chapter 10.

11. Molecular Structure (2 hours)

    Chapter 11.

4 Astronomical Techniques, AA 377 (AUG) 2:1 (45 hours)

Optional topics are given in *italics*.

4.1 Radio Techniques: 13.5 hours

1. **Introduction (1.5 hours):** Brief history of radio observations, Importance of Radio wavelength (one example), Physical mechanisms generating radio photons, Advantages of Multi-waveband observations (one example), and General description of far-field detection of radiation.

2. **Theory behind Signal Processing and Receivers (1.5 hours):** Probability Density, Expectation Values, Ergodicity, Auto-correlation and power spectrum, linear systems, Filters, digitization and sampling, square law detectors, *and other signal processing.*

3. **Antenna and Receivers (2.5 hours):** Practical aspects of Antenna, single dish observations, Coherent Receivers, Noise uncertainties, Stability, and Calibration, *and front and back-ends currently in use.*

4. **Imaging principle interferometry (1.5 hours):** resolution, aperture synthesis, method of cleaning (CLEAN) the data, and an example (*VLBI, VLA, GMRT, and others.*)

5. **Spectroscopy and Polarimetry (1.5 hours):** Radio spectroscopy principles, Theory behind the polarization detection, *Dynamic Spectra, instrumental polarization and its correction.*

6. **Future Prospectus (0.5 hours):** Future ground and space based radio telescopes (one example)

7. **Observation/data analysis laboratory (4.5 hours):**
   (a) Designing different types of radio antennas for astronomy applications.
   (b) Design / Characterization of various analog front-end modules.
   (c) Design / Characterization of various digital backend systems.
   (d) Development of simple software for simulation (of various parameters of antennas), data reduction, analysis, etc.

   Recommended references: [16], [17], [18], and [19].

4.2 IR/Optical/UV Techniques: 18 hours

1. **Introduction (1.5 hours):** Brief history of IR/Optical/UV observations, Importance of this wavelength band with an example, Physical mechanisms behind the generation of photons in this waveband, Advantages of Multi-waveband observations with an example.

2. **Detectors and optimization parameters (2.0 hours):** Optical Photo-multipliers, CCD, CMOS. IR: Thermal and quantum type detectors. UV: scintillators, MCP. Definition and estimation of signal-to-noise ratio SNR). Definition and Estimation of sensitivity/detectivity, *Statistics of Poisson processes and White noise, Optimization of SNR.*

3. **Telescopes and Imaging (1.5 hours):** Physics of image formation, Aberrations, Reflection and Refraction-type telescopes, Mounting systems, *Reflector type telescopes: prime-focus, Newtonian, Cassegrain, Ritchey-Chretien, Coude system, Schmidt cameras*, estimation of point spread function (PSF), Atmospheric turbulence and image degradation

4. **Interferometry (1.5 hours):** Michelson Stellar interferometer, Intensity interferometer, speckle interferometry, *speckle reduction techniques.*

5. **Adaptive Optics (1.5 hours):** wavefront sensors, *detectors used*, day-time and night-time adaptive optics (AO), Laser based artificial stars, Estimation of AO corrected PSF, *multi-conjugate adaptive optics, post-processing techniques: de-convolution techniques and phase-diversity*.

6. **Photometry (1.0 hours):** Photometers, observing techniques, filter parameters, estimation of typical stellar parameters using photometry, photon-counting mode.

7. **Spectroscopy (1.5 hours):** Grating, prism, and interferometer based spectroscopy, *integral field unit, image slicer*, and fiber-optics spectroscopy (multi-object spectroscopy), estimation of typical stellar parameters using spectroscopy.

8. **Polarimetry (1.5 hours):** Polarization detection techniques for Optical and IR, UV polarimetry, *instrumental polarization estimation and its correction*, estimation of typical stellar parameters using polarimetry.

9. **Observation and data reduction - Some experiments from this long-list will be chosen by the instructor(s) as per requirements and availability of resources (6 hours)**
   (a) CCD characterisation
   (b) Measurement of atmospheric extinction
   (c) Measurement of binary separations and position angles
   (d) Measurement of speckles
   (e) Wavelength calibration of spectra
   (f) Differential photometry
   (g) Determining effective temperature of a star by B-V photometry
   (h) Measurement of sky brightness / background

10. These could be done using archival data mainly from IIA telescopes:
   (a) Determining spectral type of a star
   (b) Two-colour diagrams
   (c) Extinction to a star cluster

Recommended references: [14], [19], and [13].

4.3 X-rays/Gamma-rays: 13.5 hours

1. **Introduction (1.5 hours):** History of X-ray/Gamma-ray observations, Importance of this wavelength band with an example, Physical mechanisms behind the generation of photons, Advantage of Multi-band observations with an example.

2. **Detectors (3.0 hours):** Interaction of radiation with matter, Gas-based detectors used in Astronomy, Solid-state detectors, CCDs, Micro-calorimeters, Scintillation detectors, definition and estimation of signal-to-noise ratio (SNR), *SNR optimization*, definition and estimation of sensitivity/detectivity, *statistics of Poisson processes and white noise*, background, shielding, coincidence technique, escape peak and detector response.

3. **Imaging (1.5 hours):** Grazing incidence imaging, coded mask imaging, resolution and image identification, Occultation, **imaging techniques for high energy**, Future planned imaging instruments.

4. **Spectroscopy (1.5 hours):** pulse processing, pulse-height spectra, energy-channel calibration, *importance of detector response*, Future planned spectroscopic instruments.

5. **Polarimetry (1.5 hours):** Polarization detection principle, *critical parameter optimization*, Future planned polarimetric instruments.

6. **Co-ordinated laboratory/data analysis exercises in each of the three areas (4.5 hours):**

   (a) Escape peak identification

   (b) Energy-channel calibration

   (c) Energy-resolution calibration

Recommended references: [14], [22], [15], [21], and [20].

References

[1] A. Rai Choudhuri: Astrophysics for Physicists

[2] Carroll B. W. & Ostle, D. A.: An introduction to Modern Astrophysics, Pearson Education-Addison Wesley, 2007

[3] Shu, F.: The Physical Universe, University of California, 1982

[4] Harwit, M.: Astrophysical Concepts, 3rd ed, Springer-verlag, 2006

[5] Maoz, D.: Astrophysics in a nutshell, Princeton University Press, 2006

[6] Padmanabhan,T: Invitation to Astrophyiscs, World Scientific, 2006.

[7] Acheson: Elementary Fluid Dynamics

[8] A. Rai Choudhuri: The Physics of Fluids and Plasmas

[9] R. Blandford & K. Thorne: Application of Classical Physics; `http://www.pma.caltech.edu/Courses/ph136/yr2011/`

[10] Landau & Lifshitz: Fluid Mechanics

[11] R. Kulsrud: Plasma Physics for Astrophysics

[12] G. Rybicki & A. Lightman: Radiative Processes in Astrophysics

[13] Roy, A.E. and Clarke, D.: Astronomy Principles and Practice

[14] Kitchin, C.R.: Astrophysical Techniques

[15] Knoll, G.F.: Radiation Detection and Measurement

[16] J. D. Krauss: Radio Astronomy

[17] A. R. Thompson, J. M. Moron & G. W. Swanson: Interferometry & Synthesis in Radio Astronomy

[18] Hamaker et al. (A & A Suppl. Ser., 117, 1996): Understanding Radio Polarimetry

[19] Jaap Tinbergen: Astronomical Polarimetry

[20] F. Seward & P. Charles: Exploring the X-ray Universe Cambridge Univ. Press, 2010

[21] Trumper & Hasinger (Eds.): The Universe in X-rays Astronomy & Astrphysics Library, Springer-Verlag, 2008

[22] H. Bradt: Astronomy Methods Cambridge Univ. Press, 2004