PHY669: Astronomical Techniques

[Cr:4, Lc:3, Tt:1, Lb:0]

Course Outline Pre-requisites Knowledge of IDC 201, PHY303, PHY401, PHY411 and PHY637.

1. Introduction to High Energy Astrophysics: Interactions of high energy photons: Photoelectric absorption, Photons and the atmosphere
2. Optical/IR Telescopes: Angular Magnification, Refractive and reflective telescopes and properties, Telescope Mounting (equatorial & Alt-Azimuth), Plate scale, Field of view, Resolution and Diffraction limit, Seeing (turbulence), Atmospheric windows, filters (broad and narrow; prism and gratings), effective bandwidth, magnitude and photometric system, Absolute and bolometirc magnitudes, extinction and redenning, calibration, Adaptive optics and Interferometry.
3. Optical & IR detectors Detectors: Photomultipliers, Charge Coupl Devices, Challenges and issues at infra-red wavelengths, IR bolometers, Cooling, Signal to noise (Detection limit), Sky background, flat fielding, linearity and efficiencies, etc
4. X-ray Telescopes: Basics of X-ray reflection, Types of X-ray telescopes: From Einstein Observatory to Athena, lobster optics, Fresnel Lenses
5. X-ray and γ-ray Detectors: Non-Dispersive: Position sensitive Proportional counter, Charge Coupled Device for X-ray Astronomy; Calorimeters, Transition edge sensors for X-ray astronomy; Scintillators for Gamma-rays, Spark chamber detection of electron–positron pairs; Polarization detection. Dispersive: X-ray Reflection and Transmission Gratings, Crystal Spectrometers
6. Signals in Radio Astronomy, Single dish antenna, flow of signal and components, antenna pattern, primary beam, bandwidth, sensitivity, absolute and relative measurements, signal to noise ratio.
7. Two element interferometer, baseline, time delay, response to quasi-monochromatic radiation, fringes. The Van-Cittert-Zernike Theorem, Aperture synthesis. Sensitivity, Calibration.
8. High Energy Astronomy beyond photons: Neutrino and muons detection - Galium, Cerenkov detectors, Super Kamikonde, Air showers, Auger project etc.
9. Review of Astrophysical Processes and Spectroscopy & examples: Hot plasmas: Atomic processes and line emission Stellar coronae, Supernova remnants, Hot intracluster medium and Sunyaev–Zeldovich effect Blackbody Radiation and Accretion Disks: CVs, NS and BH XRBs, and AGN Synchrotron Radiation and X-ray Polarization: Pulsars and AGN Inverse Compton Scattering: AGN SEDs
10. Multi-messenger astronomy: Gravitational Waves, detectors, detections and implications. Neutrino astronomy, detectors, solar neutrinos, neutrinos from other sources, atmospheric neutrinos. Improved modelling of sources with data from multiple messengers

11. **Lab/Hands On Sessions:** Data Analysis of topics in X-ray Astronomy: Detector background and detection sensitivity, South Alantic Anomaly; Imaging, Spectral, Timing analysis: Stars, Accreting Binaries (WD, NS,BH), SNRs, Clusters of galaxies, AGN and X-ray background. Optical: Differential photometry and spectroscopy. Radio: Single dish astronomy, pulsar observations, emission line spectroscopy. Imaging with interferometers.

Suggested Reading

1. *Astronomy Methods: A Physical Approach to Astronomical Observations*, Hale Bradt, Cambridge University Press 2003

2. *Astrophysics Processes: The Physics Of Astronomical Phenomena*, Hale Bradt, Cambridge University Press 2004

3. *X-ray Detectors in Astronomy* G. W. Fraser, Cambridge Astrophysics Series, Cambridge University Press 2009

4. *Exploring the X-ray Universe*, F.D. Seward & P.A. Charles, Cambridge University Press 2010

5. *X-ray Astronomy*, R. Giacconi & H. Gursky, Astrophysics and Space Science Library, 1974, Springer.

6. *High Energy Astrophysics*, Malcolm S. Longair, Cambridge University Press, 2011, 3rd edition

7. *Accretion Power in Astrophysics*, Third Edition J. Frank, A. King, & D. Raine Cambridge Univ Press; 2002

8. *Data Reduction and Error Analysis for the Physical Sciences*, Philip Bevington, D. Keith Robinson McGraw-Hill Education, 2003

9. Astrophysical Techniques, C. R. Kitchin, CRC Press; CRC Press; 7th edition (July 27, 2020)

10. Telescopes and Techniques, C. R. Kitchin, Springer; 3rd Edition (October 2012)

11. Astroparticle Physics, Claus Grupen, Springer, 2020

PHY6XX: Astrostatistics

[Cr:4, Lc:3, Tt:0, Lb:1]

Course Outline

- Review of Measurement & Statistics: Error (statistical, systematic) – Instrumental noise, Statistical fluctuation noise; Uncertainty, Precision and Accuracy, error-propagation and limitations
- Probability (review): Probability basics and different approaches, Conditional probability, Bayes theorem; Statistics: Bias, reliability, robustness, significance; Discrete and Continuous probability distribution functions & characterization – expectation; Moments of a distribution, Mean, median, mode, quantile; Variance; standard deviation; Skewness, Kurtosis; cumulative distribution function
- Common distribution functions (PDFs): Uniform; Gaussian; log-normal; Binomial distribution; Poisson distribution; Chi-square distribution; Beta; Student t-distribution; Cuchy (Lorentzian) distribution; Pareto distribution; central limit theorem; Multi-variate Gaussian – variance, Co-variance; correlation coefficients – linear (Pearson) and non-parametric (Spearman, Kendall);
- Gaussian random fields, definition and generation. characterization of a Gaussian random field using power spectrum. Moments and descriptions of deviations from Gaussianity.
- Pseudo Random numbers – generators and sampling; Data Simulation; Instrumental effects; Noise; Convolution; Sampling; Interpolation*; De-convolution; Application and examples
- Modeling Data: Forward and reverse modeling; Statistical inferences: classical (frequentist) and Bayesian approach; Classical: maximum-likelihood, least-square, and chi-square, parameter estimation and confidence; measurement significance; Goodness of fit and Model comparison; Hypothesis testing, F-test; KS-test; uncertainties via non-parametric ways – Boostrap & jackknife; least-square with uncertainties on both dependent and independent variables; cautions and optimization methods (LM, Simplex)
- Bayesian: basics; Prior and conjugate priors; Parameter estimation examples; nuisance parameters and marginalization
- Markov Chain Monte Carlo (MCMC) – algorithm, sampling and samplers (Metropolis-Hastings, Gibbs, Affine-invariant); diagnostics – chain inspection; acceptance fraction; Trace plots; Auto-correlation length; Hierarchical models
- Model Comparison and Hypothesis testing: Simulation and comparison; Information Criterion (Akaike (AIC) & Bayesian (BIC) Information Criterion); Odd ratio; Bayes-factor; Cross-validation; Regularization; Outliers and interquartile range
- Dimensionality Reduction: Linear Descriminant Analysis (LDA); Principle Component Analysis (PCA); Independent Component Analysis (IDA); Non-negative matrix factorization

- Time Series: trends; variability; stationarity and tests; Auto and Cross-correlation; Fourier analysis, wavelet method (temporally localized signal), Lomb Scargle periodogram

- Stochastic processes; Auto-regressive models; Moving averages; Power-spectral density; Auto-correlation; White/red/pink noise – simulating time series and confidence estimation; Unevenly sampled data

- Big data: surveys, query and access; cross-matching (TOPCAT), sigma-clipping, parallel processing, Applications with examples

Lab/Hands On Sessions:

- Data Analysis of topics in X-ray Astronomy: Spectral and Timing analysis: Stars, Accreting Binaries (WD, NS,BH), SNRs, Clusters of galaxies, and AGN (4S), differential and aperture photometry, spectroscopy, Survey data

Suggested Reading

- *Practical Bayesian Inference: A Primer for Physical Scientists*, Coryn A. L. Bailer-Jones, Cambridge University Press 2017

- *Practical Statistics for Astronomers*, Wall and Jenkins, Cambridge University Press, 2003

- *Statistics, Data Mining, and Machine Learning in Astronomy*, Željko, Andrew, Jacob, and Gray. Princeton University Press, 2012

- A First Course In Mathematical Statistics by Weatherburn,C.E.

- *Data Analysis Recipes (yet to be completed) by Hogg et. al.* – Data analysis recipes: Choosing the binning for a histogram (https://arxiv.org/abs/0807.4820) – Data analysis recipes: Fitting a model to data (https://arxiv.org/abs/1008.4686) – Data analysis recipes: Probability calculus for inference (https://arxiv.org/abs/1205.44 – Data analysis recipes: Using Markov Chain Monte Carlo (https://arxiv.org/abs/1710.0 – Data Analysis Recipes: Products of multivariate Gaussians in Bayesian inferences (https://arxiv.org/abs/2005.14199)

- *Book for Apps for Statistical Teaching*, PennState Eberly College of Science – a good online interactive learning tool

- *Data Reduction and Error Analysis for the Physical Sciences*, Philip Bevington, D. Keith Robinson McGraw-Hill Education, 2003