
The Physics of the Interstellar Medium

Summary: This course is intended to give its students a broad knowledge of how the various constituents of the Interstellar Medium (ISM) interact physically with each other. A detailed outline of the topics to be discussed is provided beginning on the next page. The course will have bi-weekly meetings, and will rely on student preparation and participation.

Prerequisites: Familiarity with Radiative Transfer; good knowledge of Quantum Mechanics; familiarity with Basic Astronomy.

Readings: Sections of texts will be assigned with each Problem Set and will be on reserve in Wolbach Library. In addition, seminal and/or recent relevant journal articles will be assigned, and will be used in class as a launching point for discussion.

Course Meetings: Two 1.5-hour meetings per week. Students should read the assigned journal articles & review the relevant text sections as the course progresses. Much of the “lecture” time will be spent in discussion. Normally, Tuesday meetings will be “lecture”-style, Thursdays will be half lecture, half discussion. *The discussions will focus on one relevant research article, and will be led by a different student each week.* Lecture notes will be posted to the course Web site after each class.

Guest Lectures: Approximately four times during the term, ISM experts from the CfA will give a guest lecture on their specialty. These lectures will cover material already listed in the syllabus below.

Problem Sets: Approximately every two weeks. Problems will cover the “basics,” along with more in-depth questions which will often require some research in the literature. Several of the problems will be based on the journal articles which form part of the assigned readings.

Exams: The course will have a take-home final exam, and no in-class exams.

Grading: 40% final exam; 35% problem sets; 25% Journal presentation

Course Web Site: <http://cfa-www.harvard.edu/~agoodman/astro208.html> Links to problem sets, reading assignments, WWW links relevant to the course, and some lecture notes will be posted here.

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1. INTRODUCTION: DEFINING FEATURES OF “A” GALACTIC ISM

1.1. EARLIEST OBSERVATIONS

1.2. THE “MODERN” VIEW & HOW WE GOT IT

- a. Composition
 - Gas, Dust, Electrons, Cosmic Rays, Photons
- b. Extent
 - Scale Height & Radial Distribution
 - Interstellar “Clouds”
 - Extragalactic Perspective
 - Comparison with Stellar Distribution
- c. Temperature Structure
 - The “Hot,” “Cold,” and “Warm” ISM
- d. Ionization State
 - Interactions with of ISM & Stars
 - example: Strömgren Sphere Analysis
 - Influence of Cosmic Rays
- e. Density Structure
 - Measures of Column Density and Volume Density
 - Hierarchy of Interstellar “Clouds”
- f. Velocity Structure
 - Galactic Scales
 - Within Individual “Clouds”
- g. Magnetic Field Structure
 - Flux-freezing & Ambipolar Diffusion
 - Measurement Techniques
 - Confinement of Cosmic Rays & “Support” of Clouds
- h. Time Scales & Stability
 - Virial Equilibrium
 - Instabilities (e.g. Jeans)

1.3. NATURE OF THE ISM: ABOVE “VARIABLES” INSEPARABLE

2. KINETIC EQUILIBRIUM & RADIATIVE PROCESSES: OVERVIEW

2.1. THERMODYNAMIC EQUILIBRIUM

- a. Partition Function
 - Kinetic, Excitation, Color, Antenna, Bolometric, and Other “Temperatures”
- b. Non-equilibrium Distributions

2.2. EXCITATION PROCESSES

- a. Collisional
- b. Recombination
- c. Non-LTE (Pumping)

2.3. RADIATIVE PROCESSES

- a. Radiative Transfer Definitions
- b. Emission & Absorption Coefficients
- c. Continuum Emission
 - Thermal
 - Bremsstrahlung & Synchrotron
- d. Scattering Processes
- e. The Influence of Shocks
 - In SNe, Star-forming Regions, and in Accretion Disks (more below)
- f. What combination of the above will be observed where?
 - Depends on l.o.s. Temperature, Density, Abundance, and Velocity Distribution

2.4. TRACING DENSITY

- a. Forbidden Lines
- b. “Critical Density” Analysis

3. THE ISM OF THE MILKY WAY

3.1. THE MULTI-PHASE PARADIGM

- a. Basic Assumptions
- b. Pressure, Mass, and Energy Balance
- c. Time Dependence

3.2. THE “COLD” ISM

- a. Atomic Gas (H I)
 - Origin of the 21-cm Line: Flipping a Spin
 - line Surveys
 - High-Velocity and High-Latitude Clouds
 - . Detection
 - . Origin & Evolution
- b. Molecular Gas
 - The Difficulty in Directly Observing H₂
 - Role of “Trace” Species
 - . Molecular Line Mapping
 - . Masers (more in AGN discussion)

3.3. DUST

- a. What is dust?
 - Cause of interstellar extinction
 - Range of Sizes from “Big Molecules” to Planetesimals
- b. Measured/Measurable Properties
 - Optical Efficiency Factors
 - . Cross-sections for emission, absorption & scattering
 - . Albedo
 - Extinction as a function of λ
 - . Total-to-Selective Extinction
 - . Spectral “features”
 - Thermal Emission as a function of λ

- . Is the blackbody approximation adequate?
 - . Are grains fractal?
 - Polarization as a function of λ
 - . Polarization due to Scattering
 - . Polarization due to Aligned Grains
 - c. Using Polarization to Map B
 - Polarization of Background Starlight
 - Polarization of Thermal Emission
- 3.4. MOLECULES & DUST TOGETHER
- a. Formation of Molecules
 - on Dust
 - in the Gas Phase
 - b. Destruction of Molecules
 - by cosmic rays
 - by photons
 - by electrons & collisions
- 3.5. HEATING & COOLING
- a. Atomic & Molecular Coolants
 - b. Dust Heating & Cooling
- 3.6. THE “HOT” ISM
- a. The Warm Neutral Medium: Broad H I lines
 - b. The Warm Ionized Medium: Absorption Line Observations
 - c. Radio Continuum Emission & Pulsars as Probes
 - Distinguishing Bremsstrahlung from Synchrotron from Thermal Emission
 - Polarization of Synchrotron Emission
 - Rotation and Dispersion Measure
 - . Faraday Rotation
 - . RM/DM of Pulsars as a Probe of B
- 3.7. X-RAYS AS A “PROBE” OF THE ISM
- a. X-ray “Shadows” of Molecular Clouds
 - b. Calibration of the CO/H₂ ratio (a.k.a. the “X-factor”)
- 3.8. HOW APPROPRIATE ARE MULTI-PHASE MODELS?
- 4. INTERACTION OF PHOTONS WITH THE ISM**
- 4.1. H II REGIONS & PHOTON-DOMINATED REGIONS
- a. Strömgren Spheres
 - b. “Clumpy” H II Regions
 - c. Radio Recombination Lines
 - d. General Shock Physics (Basic Equations, More Later)
 - e. Compact and Ultra-Compact H II Regions
 - Cometary H II Regions & Bow shock models
- 4.2. CHAMPAGNE-FLOW MODELS

- 4.3. IONIZATION FRACTION & CHEMICAL BALANCE IN PDRS
 - a. Measurements & Theories
 - b. Effects on Ion-Neutral Coupling
- 4.4. THE EFFECT OF HIGH-ENERGY PHOTONS ON MOLECULAR CLOUDS (E.G. IN AGNE)

5. STAR FORMATION IN MOLECULAR CLOUDS

- 5.1. GIANT MOLECULAR CLOUDS, DARK CLOUDS, CLOUD CORES
- 5.2. CLOUD SUPPORT & DYNAMICS
 - a. “Larson’s Laws” & Virial Equilibrium
 - Role of Magnetic Fields (Part I)
 - b. Pressure Confinement
 - c. Self-similar Structure
 - d. Rotation
- 5.3. THE ROLE OF MAGNETIC FIELDS IN STAR-FORMING REGIONS (PART II)
 - a. What matters: Static Fields, Turbulence and/or Waves?
 - b. Measurements of Field Strength
 - Zeeman Observations
 - c. Measurements of Field Structure
 - Polarization due to Aligned Grains
 - d. MHD Simulations
- 5.4. JETS & OUTFLOWS
 - a. Observed Properties of Outflows (on ~pc scales)
 - Comparison of Outflow Mechanical Luminosity & Protostar’s Luminosity
 - Aspect Ratio
 - “Hubble Flow”
 - b. Observed Properties of Jets (on ~0.1 pc scales)
 - Emission from Herbig-Haro Objects and “Shocked” H₂
 - . Continuum and Line Radiation Produced in Shocks
 - . Temperature, Ionization & Velocity Structure of Jets
 - c. Energy dissipated: Part I
 - d. Collimation Mechanism
 - The “X-celerator Model”
 - Other proposals
 - e. Jet-driven Outflows
 - (M)HD Simulations of Jets & Outflows
 - . Structure in the Momentum-Conserving Case
 - f. Origin of the Relevant B-field: Stellar or Interstellar?
 - FU Orionis Activity & Episodic Jets: Magnetic Variability?
- 5.5. DISKS
 - a. Radiated Spectrum & Dependence on Viewing Angle
 - The Role of Scattered Light

- b. Fragmentation & Instabilities
 - c. Planet Formation
- 5.6. WHAT DETERMINES THE INITIAL MASS FUNCTION OF STARS?
 - a. Agglomeration Theories
 - b. Fragmentation Scenarios
 - c. “Fractal” Scenarios & Speculation
- 6. INTERACTION OF STELLAR WINDS WITH THE ISM**
 - 6.1. WINDS FROM YOUNG STARS
 - a. Energetics: Part II
 - b. Chemical Effects
 - 6.2. WINDS FROM MAIN SEQUENCE & EVOLVED STARS
 - a. Production of Dust
 - Variety
 - Subsequent Processing to Produce Observed I-S Dust
 - 6.3. PLANETARY NEBULAE
 - 6.4. SUPERNOVA REMNANTS
 - a. Observations
 - Multi-Wavelength Radiation
 - . Optical Line & Continuum Emission
 - . Synchrotron Radiation
 - b. Shock Physics & Chemistry
 - Time Evolution: Phases in the Expansion
 - c. Energy Deposited into ISM
 - d. Simulations
- 7. THE ISM IN EXTERNAL GALAXIES AT $z \sim 0$**
 - 7.1. STRUCTURAL VARIATIONS
 - a. Density Structure
 - b. Velocity Structure & Rotation Curves
 - c. Magnetic Field Structure
 - 7.2. METALLICITY VARIATIONS
 - 7.3. MASER OBSERVATIONS OF AGNE
- 8. THE INTERGALACTIC MEDIUM**
 - 8.1. OBSERVATIONS: PRESENT & FUTURE
 - a. Gas
 - b. Dust
 - c. Magnetic Fields

8.2. RELATIONSHIP OF THE ISM & IGM

- a. Coronal Gas?
- b. Intracluster Gas in Galaxy Clusters

9. THE “ISM” AT $z \gg 0$

9.1. POSSIBLE OBSERVATIONS

- a. H I
- b. CO
- c. Future Prospects

9.2. COSMOLOGICAL PREDICTIONS

- a. Lower Metallicity?
- b. Origin of the Intergalactic & Interstellar Magnetic Fields
- c. Observational Feasibility Estimates

9.3. POLARIZATION OF THE MICROWAVE BACKGROUND

Notes:

- Specific “historical” lectures are not included in this outline. Instead, I will incorporate an historical perspective into topical lectures, whenever it is appropriate. For example, in presenting what appear to be “simple models” like the Strömgren sphere or Jeans collapse, I will discuss the observations Strömgren or Jeans would have had available at the time they made their models.
- Similarly, specific “observational technique” lectures are not included. Techniques will be discussed in context.