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: Occasionally 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/ Links to problem sets, reading assignments, WWW links relevant to the course, and 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

3. The ISM of the Milky Way

3.1. Introduction: The Multi-Phase Paradigm

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

3.2. The "Cold" ISM

a. History and Definitions
- "Out the window"
- Permitted and Forbidden Transitions
- Critical Density

b. Atomic Gas (H I)
- Origin of the 21-cm Line: Flipping a Spin
- 21-cm line Surveys
  - Collisional Excitation
  - Optical Depth Considerations
- High-Velocity and High-Latitude Clouds
  - Detection
  - Origin & Evolution

c. Molecular Gas
- The Difficulty in Directly Observing H_2
- 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/H_2 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
f. Champagne-flow models

4.2. Heating and Cooling in H II Regions

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 & the "Modern" Star Formation Paradigm

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
c. Measurements of Field Structure
d. MHD Simulations

5.4. Disks

a. Radiated Spectrum & Dependence on Viewing Angle
  - The Role of Scattered Light
b. Fragmentation & Instabilities
c. Planet Formation

5.5. Infall & Outflow

a. Expectations & Observations of Inflow
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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. 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

d. Collimation Mechanism
- The "X-wind Model"
- Other proposals
- Origin of the Relevant B-field: Stellar or Interstellar?

e. Jet-driven Outflows
- (M)HD Simulations of Jets & Outflows

f. FU Orionis Activity & Episodic Jets: Magnetic Variability?

6.2. MASS LOSS FROM MAIN SEQUENCE & EVOLVED STARS

a. Production of Dust
- Variety
- Subsequent Processing to Produce Observed I-S Dust

b. Planetary Nebulae

6.3. 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~0

7.1. VARIATIONS WITH THE REALM OF "NORMAL" GALAXIES

a. Density Structure

b. Velocity Structure & Rotation Curves
- Origin of High-velocity Clouds

c. Metallicity Variations

d. Magnetic Field Structure

7.2. "ACTIVE" AND "STARBURST" GALAXIES

a. The Cause(s) of Starbursts
b. Jets and Disks in AGNe

8. THE INTERGALACTIC MEDIUM

8.1. OBSERVATIONS: PRESENT & FUTURE

a. Lyman-α clouds, Lyman Limit systems and the Lyman Forest
b. Metal-line systems

8.2. RELATIONSHIP OF THE ISM & IGM

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

9. THE "ISM" AT Z>>0

9.1. OBSERVATIONS

a. Highly Redshifted CO
b. Future Prospects: Other lines, other techniques

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.