PY4A04 Senior Sophister
Interstellar and Intergalactic Medium

Dr Graham M. Harper: School of Physics, SNIAM 3.03a

Michaelmas and Hilary Term 2011
MT Weeks 10-13 Mon 12:00-13:00 & Wed 14:00-15:00 SNIAM Lecture Room
HT Weeks 4-6, 8-9,11, Monday 16:00-17:00 SNIAM Lecture Theatre

Class Expectations

- 12 Lectures (PY4A04 midule)
- Reading assignments completed before class.
- Final examination/Continuous assessment =50%+50%
  - 1st in January, 2nd after midule: 1 week to complete
- Tutorials as needed, and individual assessment review
- Class participation strongly encouraged
- Professional conduct
- No cell phones (laptops are OK if they are NOT disruptive)
- Office hours: SNIAM room 3.03a
  - TBD, other times by email appointment
Overview (Lectures 1-6)

- Constituents of the Interstellar & Intergalactic Medium (ISM & IGM)
  - what are the ISM & IGM?
  - images of multi-wavelength galaxy
  - some constituents of the ISM & IGM
- How do we learn about the nature of the ISM & IGM?
  - imaging and spectroscopy
  - equation of Radiative Transfer
- Atomic Processes
  - collisional excitation
  - heating and cooling (atomic and molecular)
  - thermostatic properties
- Molecules and dust grains
  - the problem of dust and molecule formation
  - observing ISM dust
  - properties of ISM grains
- “Coexisting Phases of the ISM”

Overview (Lectures 6-12)

- Photoionization (H II) regions
- Gas dynamics
  - conservation principles, Rankine-Hugoniot conditions
  - wind-ISM interactions (Mira & Betelgeuse)
- Shock waves (time scales)
  - adiabatic
  - radiating
- Supernovae
  - multiple evolutionary phases
  - interaction with the ISM
Views of the Galaxy & Astronomy Units

• Multi-wavelength Astronomy
  • observations at different λ’s provide a deeper understanding

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>SI Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>milli</td>
<td>m</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>kilo</td>
<td>k</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>mega</td>
<td>M</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>giga</td>
<td>G</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>tera</td>
<td>T</td>
<td>$10^{-12}$</td>
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</table>

<table>
<thead>
<tr>
<th>Unit</th>
<th>Description</th>
<th>SI Value</th>
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</thead>
<tbody>
<tr>
<td>Å</td>
<td>Ångstrom</td>
<td>$10^{-10}$ m</td>
</tr>
<tr>
<td>nm</td>
<td>nanometer</td>
<td>$10^{-9}$ m</td>
</tr>
<tr>
<td>μm</td>
<td>micrometer</td>
<td>$10^{-6}$ m</td>
</tr>
<tr>
<td>cm</td>
<td>centimeter</td>
<td>$10^{-2}$ m</td>
</tr>
</tbody>
</table>

Doppler Shifts (refresher)

- Line of sight velocity information
  - Observed radiation at frequency $\nu$, then if an atom is moving at velocity $v$, it is absorbing/emitting at a frequency (first order Doppler effect)
    $$\nu - \nu\left(\frac{v}{c}\right) = \nu(1 - \frac{v}{c}) = \nu - \Delta \nu$$
  - Convention: material is moving away from the observer the velocity $v$ is ‘ive (red-shifted, so frequency decreases) - ‘ive is blue-shifted
  - Astronomers use $\nu$, $\nu$, $\lambda$ interchangeably.
    $$\frac{\Delta \nu}{\nu} = \frac{\Delta \nu}{c} = \frac{\Delta \lambda}{\lambda}$$
Telescopes, some examples

- Radio m/cm (ground level): Very Large Array, large single dish (Jodrell)
- Radio mm: Atacama Large Millimeter Array @ 5000 m (Chile 2012)
- Far infrared (space): Herschel, Planck, (airborne SOFIA)
- Mid infrared (space IRAS, Spitzer COBE) (airborne SOFIA)
- Near/mid infrared (ground): Mauna Kea @ 4200 m
- Optical (sea level)
- Near/Far/Extreme Ultraviolet (space IUE, HST, FUSE, EUVE)
- X-ray/Gamma Ray (space Fermi) (ground Cerenkov)
- Cosmic rays and neutrinos: e.g., IceCube Neutrino Observatory
Spiral galaxy seen from better angle

M83 Ultraviolet GALEX 2-colour image showing star formation far from where expected: red 21-cm radio shows extended spiral arms

Very Local ISM

Remarkable new results from Interstellar Boundary Explorer (IBEX)
ENA's = Energetic Neutral Atoms

Voyager 1 and 2 missed the belt!
**Local ISM**

Credit: (former CU graduate student) Seth Redfield

**Local context**

**Local Bubble**

- $R \sim 100$ pc; $n_e \sim 10^{-3}$ cm$^{-3}$; $T \sim 10^6$ K
- Absence of cold material (NaI spectroscopy)
- Soft X-rays (0.25 keV)
- Highly ionized absorption and emission lines (e.g., OVI, OVII, OVIII)

**LISM**

- $R \sim 1-10$ pc; $n \sim 0.2$ cm$^{-3}$; $T \sim 7000$ K
- He I particles (Ulysses; in situ)
- Backscattered Lyman-$\alpha$ emission
- Absorption line spectroscopy of neutral and singly ionized elements, e.g., H$\alpha$, Ni I, Ol, St I, Ne I, Ne II, He II, Ne II, Ne III, He I, Ne IV, Ne V, Ne VI, Ne VII, Ne VIII, Ne IX, Ne X

**Cold Dense Gas**

- $R \sim 1.4$ pc; $n_H \sim 30$ cm$^{-3}$; $T \sim 20$ K
- Spectroscopy of neutral ions (e.g., NaI)
- Molecules, e.g., H$_2$, CO, alcohols (ethyl alcohol; CH$_3$CH$_2$OH), acids (formic acid; HCOOH), aldehydes (formaldehyde; H$_2$CO), ketones ((CH$_3$)$_2$CO; acetone), amino acids? (H$_2$NH$_2$CCOOH; glycine)
Stellar Nursery

- Illustrates some of the problems addressed in this course
  - obscuration by dust
  - dust heating by starlight
  - photoionized nebulae

- Illustrates that images are now becoming powerful tools for studying the ISM in detail
  - images at multiple wavelengths
  - good spatial resolution

Will “this” form a star?

- Star formation
  - Stability of cold clouds against collapse
  - Dark clouds (as small as $10^{-2} \text{ pc}$)
    - Barnard 68 – a Bok Globule (B68)
**Reflection Nebulae**

- Massive stars illuminating their environs
  - Scattering of star light by dust (albedo)
  - Scorpio-Ophiuchus reflection nebulae
    - Antares (red supergiant) is the orange nebula
    - Hot stars provide other the nebulae
Stellar life – interacting with ISM

- Hydrodynamics
  - Wind-ISM interactions
  - Mira – the marvelous –
    - a pulsating red giant, very high proper motion star = large velocity

Stellar old age – planetary nebulae

- End of red giant phase
  - Jupiter’s Ghost
  - H II Region
  - Ionization Physics
    - Strömgren sphere
    - WD
    - $10^4$ year phase
Stellar death - supernovae

- End of red supergiant phase
  - Supernova remnant
  - $10^4$ yr SMC 0103-72.6, Chandra X-ray emitting shell
  - $10^3$ yr Crab nebula (right)
  - Hot phase of ISM and element enrichment

What properties can we learn about the ISM?

- Thermodynamics
  - gas temperature
  - density and ionization
  - elemental composition
- Dynamics
  - large spatial scale velocities, i.e., shocks, winds, flows
  - small spatial scale velocities, i.e., turbulence
- ISM dust
  - dust temperature
  - ~mineralogy (composition and structure)
- Ambient radiation field
  - depends where you are in galaxy
- Galactic magnetic fields
Galactic magnetic fields

Polarization vectors (radio) follow magnetic field in the large scale spiral arms with 8 $\mu$G.

BUT highly structured magnetic fields (20 $\mu$G) also exist between the arms.

Approx. Properties of ISM phases (Tielens)

<table>
<thead>
<tr>
<th>Phase</th>
<th>Density (cm$^{-3}$)</th>
<th>Temperature (K)</th>
<th>Sound Speed (km s$^{-1}$)</th>
<th>Total Mass ($10^8 M_{\text{Solar}}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot inter-cloud</td>
<td>0.003</td>
<td>$10^6$</td>
<td>130</td>
<td>-</td>
</tr>
<tr>
<td>Warm neutral</td>
<td>0.5</td>
<td>8000</td>
<td>10</td>
<td>2.8</td>
</tr>
<tr>
<td>Warm ionized</td>
<td>0.1</td>
<td>8000</td>
<td>10</td>
<td>1.0</td>
</tr>
<tr>
<td>Cool diffuse clouds</td>
<td>50</td>
<td>80</td>
<td>1</td>
<td>2.2</td>
</tr>
<tr>
<td>Molecular clouds</td>
<td>&gt;200</td>
<td>10</td>
<td>0.4</td>
<td>1.3</td>
</tr>
<tr>
<td>H II regions</td>
<td>1 - $10^5$</td>
<td>$10^4$</td>
<td>13</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Densities are typical, but can vary by an order of magnitude.
The Interstellar Medium (ISM) is seldom homogenous!