The Physics of the Interstellar Medium

Ulrike Heiter
Contact: 471 5970
ulrike@astro.uu.se

www.astro.uu.se
Matter between stars

- Average distance between stars in solar neighbourhood: 
  \( 1 \text{ pc} = 3 \times 10^{13} \text{ km} \), average star diameter: \( 10^6 \text{ km} \)
- \( \Rightarrow \) part of space occupied by stars: \( \left( \frac{10^6}{3 \times 10^{13}} \right)^3 \)
  \( \approx 10^{-22} \)
- Upper limit for matter other than known stars
  - Oort limit = total matter density in galactic plane from gravitational acceleration of stars = \( 0.1 \text{ M}_{\odot} \text{ pc}^{-3} \)
  - Density of known stars = \( 0.05 \text{ M}_{\odot} \text{ pc}^{-3} \)
  - Upper limit for IS density = \( 10^6 \text{ atoms m}^{-3} \)
Matter between stars

- Observational evidence for matter between stars (up to 1930s):
  - Optical images: dark clouds and diffuse bright nebula
  - Photometry: Interstellar extinction and reddening
  - Spectroscopy: IS absorption lines in stellar spectra: stationary in spectroscopic binary spectra, different doppler shift, strength increasing with distance
IC 1396

Thackeray's Globules

CG 4
Trumpler (1930)

100 Open Clusters
Absorption: 0.7 mag per 1000 parsec
Extinction in the inner Galactic Bulge: comparing infrared colors and magnitudes observed for AGB and RGB stars with those predicted from stellar evolution models

Fig. 3. Map of the extinction in the inner Galactic Bulge. The image grey scale represents an $A_V$ range in magnitudes from 0 (white) to 35 (black). A coloured high resolution image can be found at http://www-denis.iap.fr/articles/extinction/
Struve (1928) Ca II K line in 1700 O-B3 stars

Fig. 6.—Relationship between intensity of detached K and distance
Red and blue light from nebulae

M 20

NGC 6559 and IC 1274-75
Interaction of stellar radiation with dusty gas clouds

Horsehead Nebula

NGC 6188 and NGC 6193
Dust in galaxies

M 65

M 100

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21cm emission line of neutral hydrogen

Intensity

Brightness Temperature, $T_b^*$ (K)

Frequency (Wavelength)

LSR Velocity (km s$^{-1}$)
Components of the ISM

- **Gas and dust**: several phases with different densities and temperatures
- **Radiation fields**: large local variations, ionization, absorption
- **Velocity fields**: large scale flows as well as turbulent small scale motions
- **Magnetic fields**
- **Cosmic rays**: high energy particles

All have comparable energy densities:
\[ \sim 1eV/cm^3 \]
## Structures within the Interstellar Medium

<table>
<thead>
<tr>
<th></th>
<th>Density [cm(^{-3})]</th>
<th>Temperature [K]</th>
<th>Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular clouds</td>
<td>&gt; 100</td>
<td>10 – 20</td>
<td>H(_2), CO, ...</td>
</tr>
<tr>
<td>Diffuse clouds</td>
<td>10 – 1000</td>
<td>80</td>
<td>HI, other atoms, dust</td>
</tr>
<tr>
<td>Warm neutral medium</td>
<td>0.1 – 10</td>
<td>8000</td>
<td>HI, other atoms</td>
</tr>
<tr>
<td>Warm ionized medium</td>
<td>0.3 – 10</td>
<td>8000</td>
<td>H(<em>{II}), N(</em>{II}), S(_{II}), ...</td>
</tr>
<tr>
<td>Hot ionized medium</td>
<td>&lt; 0.01</td>
<td>5x10(^5)</td>
<td>H(<em>{II}), OVI, NV, Si(</em>{IV})</td>
</tr>
<tr>
<td>H(_{II}) regions</td>
<td>10 – 10(^4)</td>
<td>8000</td>
<td>H(<em>{II}), O(</em>{II}), O(_{III}), ...</td>
</tr>
<tr>
<td>Ultracompact H(_{II}) regions</td>
<td>10(^4) – 3x10(^5)</td>
<td>8000</td>
<td>H(_{II})</td>
</tr>
<tr>
<td>Planetary nebulae</td>
<td>100 – 10(^4)</td>
<td>10(^4)</td>
<td>H(<em>{II}), He(</em>{II}), O(<em>{II}), O(</em>{III}), S(_{II}), ...</td>
</tr>
<tr>
<td>Supernova remnants</td>
<td>&gt; 1</td>
<td>10(^4) – 10(^7)</td>
<td>H(<em>{II}), He(</em>{II}), O(<em>{II}), O(</em>{III}), S(_{II}), ...</td>
</tr>
</tbody>
</table>

from Allen’s Astrophysical Quantities, p. 524
## Structures within the Interstellar Medium

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<thead>
<tr>
<th>Structure</th>
<th>Mass ([\text{M}_\odot])</th>
<th>Height [pc]</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular clouds</td>
<td>(10^9?)</td>
<td>40 – 60</td>
<td>radio, near-IR, near-UV</td>
</tr>
<tr>
<td>Diffuse clouds</td>
<td>(1.5 \times 10^9)</td>
<td>100</td>
<td>radio, IR, optical</td>
</tr>
<tr>
<td>Warm neutral medium</td>
<td>(1.5 \times 10^9)</td>
<td>500</td>
<td>radio, optical</td>
</tr>
<tr>
<td>Warm ionized medium</td>
<td>(10^9)</td>
<td>1000</td>
<td>optical, UV</td>
</tr>
<tr>
<td>Hot ionized medium</td>
<td>(10^8)</td>
<td>3000</td>
<td>X-ray</td>
</tr>
<tr>
<td>HII regions</td>
<td>(5 \times 10^7)</td>
<td></td>
<td>optical, IR</td>
</tr>
<tr>
<td>Ultracompact HII regions</td>
<td></td>
<td></td>
<td>radio</td>
</tr>
<tr>
<td>Planetary nebulae</td>
<td></td>
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<td>Supernova remnants</td>
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<td>radio, IR, optical, X-ray</td>
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</table>
Cartoon 2  General picture of ISM

$H$-atomic  \{ clouds  

$H_2$-molecular  

hotter & less dense intercloud medium

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DNe  
HII region  
$\sim 10^4 K$

SFR  
$10^4 K$; $10^3 m^{-3}$

Atomic cloud  
$\sim 100 K$  
\[3 \times 10^7 m^{-3}\]

Intercloud medium  
$\sim 8000 K$  
\[3 \times 10^5 m^{-3}\]  
(partially ionized)  

Hot component  
$\sim 10^6 K$  
\[10^3 m^{-3}\]  
halo  

Thin disk  
5 pc; 50 M\odot

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Molecular cloud  
$\sim 20 K$  
\[10^9 m^{-3}\]  

Halo  
20 pc
Characterstic densities

Dust: ~ 1-10% of gas mass
   grain size: 0.1 - 0.001 mm,
   ~ 1 grain/10^6 m^3
   ~ 0.001 M_{sun}/pc^3

Gas: ~ 10^6 atoms/m^3
    ~ 0.01 M_{sun}/pc^3

H: 90%, He: 10%, CNO: 0.1%

gas atoms/dust grains by number = 10^{12}
Interstellar lines

Often many components towards distant stars in the galactic plane.

- Na I D lines 589, 589.6 nm
- Ca I 422.7 nm
- Ca II H and K lines, 393.4, 396.8 nm
- 21 cm HI hfs line of $^2S_{1/2}$ ground state.
- Recombination lines
  Ionized regions show recombination spectra e.g. H I $n = 109 \rightarrow n = 108$ line at 5009 MHz etc. to Hα and Lyα
Some important molecular lines

- OH 18 cm, 4 lines
- SiO 3, 45 mm
- SO 3.02 mm, ...
- CO 2.6, 1.3, 0.87 mm
- CN 2.6 mm
- CH 9.2 cm
- CS 6.1, 3.1, 2.0 mm
- H₂O 13.5, 1.63 mm
- H₂S 1.78 mm
- NH₂⁺ 3.22 mm
- C₂H 3.4 mm, 2 lines
- NH₃ 12.6 mm, 2 lines
- HCN 3.38 mm
- HNC 3.31 mm
- HCO⁺ 3.37 mm
- H₂CO 6.21, 2.07 cm
- CH₃OH 3.1 mm, 3 lines
The Cosmic Cycle

Important:
- M
- timescales

nuclear processing

star formation

ISM; mixing; $[\frac{A}{H}] \uparrow$

gas and dust bath (ISM)

explosions

stellar remnants: WD, NS, BH

metal-enriched gas $\Rightarrow$ z increases

(Hoyle et al. 50ies)
Protostars → ISM → Young stars → Old stars

ISM

Young stars

Old stars

Protostars

ISM

PN

SNR

White dwarfs

Black holes

Neutron stars
Life cycle of stars

NGC 3603

HST • WFPC2

PRC99-20 • STScI OPO • June 1, 1999
Wolfgang Brandner (JPL/IPAC), Eva K. Grebel (Univ. Washington),
You-Hua Chu (Univ. Illinois, Urbana-Champaign) and NASA
Intimate relation between gas, dust, and young stars.
Winds from high-mass stars

Wolf-Rayet star

Henize 70 (LMC)
Winds from low-mass stars
The Egg Nebula
HH 32

Hubble's variable nebula

NGC 2346

NGC 2440
Planetary nebulae
Supernovae
How light echoes are formed. The gray areas are clouds of dust. As discussed more fully on page 25, echoes can come not only from material behind the supernova (A), but also from dust at the same distance (B) and even closer to us than the explosion (C, D, and E). Wherever these interstellar clouds intersect the inner, solid ellipse we will see a light echo two years after the supernova’s maximum light. After three years the echo ellipse has expanded to the dashed line and the echoes have moved outwards, revealing dust cloud E. For clarity the clouds of reflective particles have been drawn much closer to the supernova than they are in reality, and the ellipses and relative location of the supernova are not to scale. The ellipses are actually extremely narrow.
Supernova remnants

Pencil Nebula

Vela SNR

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Local ISM (1500 light years)

http://www.astro.uu.se/forskarutb/LISM/LISM.html

see also talk by Jeff Linsky:

http://www.astro.uu.se/forskarutb/LISM/LISM.html
EM radiation - Spectroscopy

We need:

1. Radiative transfer
2. Atomic and molecular physics (micro-physics): cooling and heating
3. Gas physics and dynamics (macro-physics): motions of ISM gases, shock fronts, IF, stellar winds, and explosions

Star

Stellar structure: optically thick

Stellar atmosphere: optical depth around 1

Sun:
\[ \rho = 10^{-7} - 10^{-10} \text{ g/cm}^3 \]
\[ P_{\text{gas}} = nkT = 10 - 10^4 \text{ N/m}^2 \]
\[ 4000 < T < 10000 \text{ K} \]
\[ \Rightarrow n = 10^{17} - 10^{14} \text{ cm}^{-3} \]

ISM:
optically thin
low density
low particle density
low pressure

- winds
- explosions
- star formation