Outline

Review

Stellar evolution/nucleosynthesis/H-R diagrams

Phases of the Interstellar Medium

The Hydrogen Atom
Evolution+nucleosynthesis – each box is a different burning stage. Could you sketch the H-R diagram of this cluster and label all of the major burning stages?

H-R diagram for 47 Tuc
Stellar initial mass function

\[ dN = N_o \ (M) \, dM \]

\[ dM \ M \ (M) = \text{total mass of burst/episode} \]

Observationally: \( (M) \) goes as \( M^{-2.35} \)

Slight variation with mass, according to some "Salpeter IMF"
Interpreting CMDs

Density of any locale on a CMD is a function of IMF, SFR, mass, and age

\[ C(M_V, V-I) = \int (\log m, t) \times SFR(t) \, dt \, d\log m \]

Small mass bin (i.e. single mass)
Constant IMF ( )
Can recover star formation history from a complex CMD

Statistical Approach

What is the probability that a certain distribution of points on the CMD came from one particular set of stellar evolution models (Tolstoy & Saha 1996)
Interstellar Matter

Optically visible components
  Dark band through center of the MW
  Diffuse emission regions

Verification
  Cluster diameter vs luminosity distances
  Non-varying absorption lines in binaries

NGC 891 – viewed edge-on
# Phases of the ISM

<table>
<thead>
<tr>
<th>Phase</th>
<th>Temp.</th>
<th>n</th>
<th>f.f.</th>
<th>Diag.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold</td>
<td>10</td>
<td>$10^4$</td>
<td>low</td>
<td>CO</td>
</tr>
<tr>
<td>Cool</td>
<td>$10^2$-$10^3$</td>
<td>$10^3$</td>
<td>low</td>
<td>HI</td>
</tr>
<tr>
<td>Warm</td>
<td>$10^3$-$10^4$</td>
<td>$10^2$</td>
<td>high</td>
<td>HI</td>
</tr>
<tr>
<td>Warm</td>
<td>$10^4$</td>
<td>10</td>
<td>high</td>
<td>H</td>
</tr>
<tr>
<td>Hot</td>
<td>$10^5$-$10^6$</td>
<td>1</td>
<td>high</td>
<td>X-ray</td>
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</table>
Detection Methods

Cold – molecular line spectroscopy with radio/mm wave telescopes.

CO has a dipole moment, transitions due to ang mo quantum number (e.g. J=1 0 at 2.6mm)

\[ I_{CO} = \text{dv} \, T_A \text{ (2.6mm line of }^{12}\text{CO}) \]

\( T_A \) is the antenna temperature so that \( P = kT_A \)

Conversion to \( \text{H}_2 \)

Assume CO linewidth is gravitational, so that the velocity dispersion is

\[ = (GM/R)^{1/2} \text{ (so } I_{CO} \text{ is proportional to mass)} \]

\[ X \, N(\text{H}_2)/I_{CO} \sim 2.3 \times 10^{24} \]

(is this really the same everywhere???)

Other methods include UV spectroscopy to get \( \text{H}_2 \), even more complex molecules (e.g. HCN)
Detection Methods – Cool, Neutral

\[ \frac{dI}{ds} = \left( \frac{h}{4} \right) [n_2 A_{21} - (n_1 B_{12} - n_2 B_{21}) (4 I /c)] \]

- \( n \) = # density of atoms
- \( A_{21} \) = prob. for spontaneous emission
- \( B_{12} \) = prob. for stimulated emission
- \( B_{21} \) = prob. for absorption

\[ \frac{dI}{d} + I = S_v (S = \text{source function}) \]

\[ I(0) = I(0)e^{-} + S(1-e^{-}) \]

Assume thermodynamic equilibrium so the source function is the Planck function and level populations is governed by:

\[ \frac{n(2)}{n(1)} = \frac{g(2)}{g(1)} \times \exp(-h /kT) \]
Cont’d

\[ A_{21} = (8 \ h \ \frac{3}{c^3})B_{21} \]

\[ g_1B_{12} = g_2B_{21} \]

Assume…

\[ h \ \ll \ kT \]

So…

\[ B_v(T) = \left(2kT \ \frac{2}{c^2}\right) \]

So….

\[ I(\ ) = I(\ 0)e^{-} + \left(2kT \ \frac{2}{c^2}\right)(1-e^{-}) \]

\[ T_B \left(\ \frac{c^2}{2k} \ 2\right)I ; \]

substitute this in and get…

\[ T_B(\ ) = T_B(0) e^{-} + (1-e^{-})T \]
Cont’d

Optically thin ( \( << 1 \))
\[
T_B = T
\]

Optically thick ( \( >> 1 \))
\[
T_B = T
\]
21 cm HI line

Hyperfine transition in the ground state from the interaction between the spins of the electron and proton.

\[ \Delta E = 6 \times 10^{-6} \text{ eV} \quad \text{freq} = 1.4204 \text{ GHz} \]

Lifetime of excited level is long (10^7 yr) so collisional excitation and de-excitation is fast compared to spontaneous decay. Level populations depend only on kinetic temperature of the gas.

**Optical depth** = \( (B_{12} h^2)^{-2/ck} N_1 / T \)

\[ N_1 = \int ds \ n_1 = \text{column density of H atoms capable of absorbing at frequency,} \]

With some more approximations and rearranging we can get a famous relationship

\[ N_H = 1.82 \times 10^{22} \ dv \ T_B \text{ (if optically thin), and} \]

\[ M_H = 2.36 \times 10^5 \ D^2 \ S(v) \ dv, \text{ where } S(v) \text{ is in Jy km s}^{-1} \]
Warm Ionized Gas

Largely yields emission lines via recombination into various primary quantum levels H (656.3nm) arises from transition from n=3 to n=2.

See example from M33

Also a few higher ionization states of heavier nuclei in the UV (e.g. CIV).
Hot Gas

Gas heated to $10^6$ K (probably by SNe)
- Powerful probe of mass distribution in galaxy clusters

Detected via X-ray emission
- Point source population
- Diffuse hot gas

Emission via
- Bremsstrahlung
- Emission lines of highly ionized species
Diffuse Hot Gas and the Soft X-Ray Background

McKee & Ostriker (1977): diffuse hot phase of the ISM with a filling factor of 100%

Early detection of X-ray emitting “superbubbles” in the Milky Way: Sco-Cen, Orion-Eridanus (McCammon et al. '83, McCammon & Sanders '90)

Origin of Soft X-Ray background

MWG: local ISM + hot galactic halo

Local Group: hot intergalactic medium

Extragalactic: (un)resolved AGN + E galaxies
The Local Bubble

Radius: 100-200 pc

Temperature: \( \sim 2 \times 10^6 \) K

Thermal pressure: \( p/k = 10^4 \text{ cm}^{-3} \text{ K} \)

\[ N(\text{HI}) = 6 \times 10^{18} \text{ cm}^{-2} \text{ (derived from soft X-ray absorption)} \]

Origin of the Local Bubble

- hot gas w/ 100% filling factor?
- diffuse gas reheated by recent SNe?
- a series of 2-5 SNe a few million years ago?
- an extension of nearby superbubble?
Comparison of X-Ray Observatories

Einstein: 1' resolution
M101 (McCammon & Sanders 1984)
$L_X$(diffuse) $\sim 10^{38}-10^{40}$ erg s$^{-1}$

ROSAT (PSPC): 1.'8 resolution, 0.1-2 keV
M101, N3184, N4395, N5055, N4736 (Cui et al. 1996)

CXO: <1” over 8 arcminutes

XMM/Newton: 15” over 30 arcminutes
So you want to work with CXO data?
Solid line – “sky”

Dashed line – instrumental background
NGC 3631

Red = X-ray emission
Spirals are best fit with two temperature models of hot gas, but there is variation in the high temperature and surface brightness.
Summary of X-Ray Results

Diffuse emission is highly correlated with both spiral arms and HII regions.

Bulk of the diffuse emission arises from less than 25% of the area of the disk.

X-ray spectra are best fit with a two temperature model.

There is variation in the surface brightnesses between galaxies and variation in the temperature of the hot component.
Impact of Massive Stars

stellar winds + SNe
dump $10^{53.5}$ erg into ISM
creates hot bubble
surrounded by swept up
ISM and circumstellar
matter – gas heated by
inward moving shock
X-ray emission should
be aligned with HI holes
growth of chimneys (as
means of getting hot gas
into the halo)

Norman & Ikeuchi
yellow = X-ray contours
grey = HI column density