The Interstellar Medium-
Overview IV
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The Molecular Milky Way
Local Star Forming Regions

- Much of our knowledge of star formation comes from a few nearby regions
  - Taurus-Auriga & Perseus
    + Low mass (solar type stars)
    + 150 pc
  - Orion
    + Massive stars (OB stars) in Orion
    + 500 pc
- How representative are these regions of the Galaxy as a whole?
Ophiuchus

Wilking et al. 1987 AJ 94 106

Ha EMISSION LINE STARS

CO

1.3mm mosaic of $\rho$ Oph main cloud

Andre PP IV
Orion

+ CS cores > 200 M☉ 
& Stellar clusters 
(Lada 1992 ApJL 393 25)
Conditions for Collapse

- Supersonic motions are observed in molecular clouds
  - Approach thermal line widths on small scales
- If cloud cores make stars, then they must be gravitationally bound
  - For thermal support
    \[ \frac{GM}{R} \sim c^2 = \frac{kT}{\mu m} \]
    
    \( c \) is the sound speed and \( \mu \approx 2.3 \) is the mean molecular
    
    \( R \approx 0.1 \left( \frac{M}{M_\odot} \right) \left( \frac{10 \text{ K}}{T} \right) \text{ pc} \)
Magnetic Fields

- 850 µm polarimetry toward B1 shows polarized continuum emission
  - Aligned grains and hence a component of the magnetic field in the plane of the sky
  - No correlation between the polarization angles measured in optical polarimetry.
- The polarized emission from the interior is consistent with OH Zeeman data if the total uniform field strength is \( \sim 30 \mu G \)
Molecular Cloud Cores

**Fragmentation & Collapse: I**

- **Jeans instability**—the dispersion relation for a perturbation \( \mathcal{D} \sim e^{i(\omega t - kx)} \) is
  \[
  \omega^2 = c^2 (k^2 - k_J^2), \quad k_J^2 = 4\pi G\rho_0 / c^2
  \]
- \( k^2 - k_J^2 < 0 \) makes \( \omega \) imaginary
  - Exponential growth when \( k < k_J \)
  - Growth rate, \(-i\omega\), increases monotonically with decreasing \( k \)
    - Longest wavelength perturbations (largest mass) grow fastest
    - Fastest collapse of the largest scales suggests fragmentation unlikely (Larson 1985 MNRAS 214 379)
**Fragmentation & Collapse: II**

- **The Virial Theorem**—dot Euler equation with $r$ and integrate over $V$

$$ 0 = \int_V 3P \, dV \int_V (\vec{r} \cdot \vec{\nabla}) \, dm \int_S P_{\text{ext}} \, \vec{r} \cdot d\vec{S} $$

$$ 0 = 3c^2 M \left\{ \frac{3GM^2}{5R} \right\} \left\{ 4R^3 P_{\text{ext}} \right\} $$

\[ P_{\text{ext}} \quad V \]
Virial Theorem

- There is a minimum radius where the cloud can no longer support itself against gravity

\[ P = \frac{3c^2 M}{4R^3} - \frac{3}{20} \frac{GM^2}{R^4} \]

- Beyond the critical point self-gravity decreases \( R \) without any help from \( P \)
- Equilibria states which require \( P \) to decrease with decreasing \( R \) are unstable
Stable and Unstable Virial Equilibria

- For a given $P$ there are two equilibria

- Squeeze the cloud at
  - Requires more pressure to confine it at its new radius
  - Re-expand (stable)

- Squeeze the cloud at $A$
  - Requires less pressure to confine it
  - Contract (unstable)
Non-Thermal Pressure

- Magnetic fields are difficult to measure in cloud cores
  - OH absorption measurements are difficult because of the small chance of a background radio source
- Single measurement of $|B| \cos \theta \approx -19 \pm 4 \mu G$ towards B1
  - OH probes $n_H \approx 10^3 \text{ cm}^{-3}$
- $B^2/8'' \sim 3 \times 10^5 \text{ K cm}^{-3}$
  - Comparable to the thermal pressure of a 10 K core with $n \sim 10^4 \text{ cm}^{-3}$


Stokes I
1667 MHz
1665 MHz
Stokes V

Antenna Temperature (K)
LSR Velocity (km/s)
Magnetized Cloud

- Assume a uniformly magnetized cloud

\[ 0 = 3c^2 M \left( \frac{3}{5} \frac{GM^2}{R} + \frac{1}{3} R^3 B^2 \right) - 4\sqrt{R^3 P} \]

Magnetic flux is

\[ \Phi = \sqrt{R^2 B} = \text{const.} \]

for a good conductor

- Gravitational and magnetic terms \( \sim 1/R \)
  - i.e., they remain in constant proportion
Protostellar Accretion

- $dM/dt \sim c^3/G$
- $M_0 = 0.01 \, M_\odot \quad R_0 = 3.5 \, R_\odot$
- $dM/dt = 10^{-5} \, M_\odot \, yr^{-1}$ for $10^5$ yr
  - Accretion shut off at 1 $M_\odot$
  - Gas photosphere cools at constant $R$ for $\sim 1$ day
  - Loiters for $\sim 3000$ yr on the 2D main-sequence
  - Followed by Hayashi contraction
- T Tauri stars have long PMS evolution
  - 10-100 Myr
- Herbig Ae/Be stars are 2-10 $M_{\odot}$
  - $t_{\text{PMS}} < 10$ Myr
- For $M > 5 \, M_{\odot}$ there is no PMS phase
  - *Birthline* indicates approximate location where YSOs become visible
The Four Stages of Star Formation

1. Initial cloud formation
2. Compression and heating
3. Rotation and accretion disk formation
4. Final star formation

Shu et al. (1987 ARAA 25 23)
SED Classification

Class I
Infall with simultaneous bipolar outflow

Class II
Visible T Tauri stars with disks & winds

Class III Circumstellar material accreted or dissipated, leaving a pre-main-sequence star, possibly with planets
Inside-Out Collapse in B335

The HH 211 Outflow

- 1.3 mm continuum
- Circumstellar disk
- $^{12}$CO 2 – 1
  - Molecular outflow
  - Top: $|v| < 10$ km/s
  - Bottom: $|v| > 10$ km/s
- H$_2$ 2.12 µm
  - Shocks
  - Gueth & Guilloteau 1999 A&A 343 571
Evolving Circumstellar Environment

- Debris disk studies suggest that the quantity of circumstellar material declines rapidly with age: $M \propto t^{-2}$
OB stars in Orion

- 450 pc
- $t < 1$-$2$ Myr
- 3500 stars within 2.5 pc radius
  - 0.1 - 50 $M_\odot$
  - 900 $M_\odot$
- A few O stars
  - Lots of low mass stars too
    (Hillenbrand 1997 AJ 113 1733)
High Mass Stars

- Evolutionary time scales for OB stars are $<\ll$ for low-mass stars
  - OB stars modify their environment soon after a stellar core has formed since their Kelvin-Helmholtz time scale
    $$t_{KH} = E/L \sim GM^2/LR$$
    $< 10^4$ yrs for an O star
- Core H-burning begins before accretion of matter from the surrounding protostellar envelope stops
- When the protostar reaches the **ZAMS**, it begins producing appreciable UV flux and (possibly) a strong wind modifying the surrounding conditions, structure, & chemistry
- The new OB star ionizes its surroundings, giving rise to a small region of ionized gas, usually referred as the **ultracompact HII** (UCHII) region phase
  - UCHII regions have diameters $< 0.05$ pc
  - **Compact** HII regions have sizes in the range 0.05-0.5 pc
Properties of Massive Stars

- Massive stars = O & B stars
- Massive stars are OB stars which ionize HII regions

<table>
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<tr>
<th>Spectral Type</th>
<th>Mass $M_{\odot}$</th>
<th>$M_V$</th>
<th>$T_{\text{eff}}$ K</th>
<th>$\log_{10} \left( \frac{Q}{\text{s}^{-1}} \right)$</th>
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<tr>
<td>O5</td>
<td>60</td>
<td>-5.6</td>
<td>48,000</td>
<td>49.7</td>
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<td>O8</td>
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<td>B0</td>
<td>18</td>
<td>-4.4</td>
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<td>47.7</td>
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Dense Gas & Massive Stars

- The hallmark of newly formed OB stars are compact and ultra-compact HII regions
- Intimately associated with warm and dense regions of molecular gas
  - G9.62+0.19
    - UC HII region
    - NH$_3$ hot core (dashed)
    - 1.3 cm continuum emission (solid)
    - H$_2$O (▲) & OH (□) masers (Kurtz PPIV)
Morphology of Compact HII Regions

- High angular resolution radio continuum observations show a variety of morphologies
  - UC HII regions in radio continuum
  - **Shell** source G45.07+0.13 (Turner & Matthews 1984)
  - **Bipolar** source NGC 7538 (Campbell 1984).
  - **Cometary** source G34.3+0.15 (Gaume et al. 1994).
Why do we see so many UC HII regions?

IRAS point source catalog & a far-IR color criterion selects UC HII
  - Wood & Churchwell (1989) counted 1650 Galactic UC HII
  - If these objects have physical parameters similar to a much smaller number of radio-observed UC HII then
    + \( R \sim 0.05 \) pc
    + \( N_U \sim 4 \times 10^{48} \) s\(^{-1}\)
    + \( n_0 \sim 10^5 \) cm\(^{-3}\)
  - Dynamical ages are typically \( \sim 5000 \) yr

Implies \( \sim 1650/5000 = 0.3 \) O stars yr\(^{-1}\)

Considerably larger than that estimated from other means
  - Typical estimates give \( 0.82 \) M\(_{\odot}\) yr\(^{-1}\) (10 < M/M\(_{\odot}\) < 60) (Güsten & Mezger 1983 or Downes 1987)
  - An IMF-weighted of \( <M_{\text{OB}} > 23 \) M\(_{\odot}\) implies \( \sim 0.04 \) O stars yr\(^{-1}\)
  - 10 times smaller than that derived from UC HII regions
Champagne Flows

- “Champagne flow” or blister models assume that the massive star is born in a medium with large density gradients

- The star evacuates a cavity of ionized gas
- At the boundary of the cloud the ionized cavity breaks out creating a flow of gas away from the cloud due to the pressure gradient between respectively the cloud and the ambient ISM
Bow Shocks

- Cometary HII regions may be stellar wind bow shocks of an ionizing star moving supersonically through a molecular cloud (Van Buren et al. 1990; MacLow et al. 1991)
  - Bow shocks explain details of the morphology
    + Limb brightening
    + Emission pinches back down to the symmetry axis
    - Not easily explained within the champagne models
Photoevaporating Disks


\[ r_g = \frac{G M_\star}{c^2} \]
A High-Mass Protostar with a Massive Rotating Disk

- The high-mass Class 0 protostar NGC 7538S has a massive rotating disk and outflow
- Resolved with the BIMA in the 3.4 mm continuum and in H$^{13}$CN
  - Nearly edge-on and has a size of 30,000 AU
  - Outflow perpendicular to the rotating disk is mapped in SiO and HCO$^+$
- H$^{13}$CN velocity gradient is consistent with Keplerian rotation orbiting a $\sim 40 M_\odot$ central object
- The mass of the continuum "disk" is 100 $M_\odot$ and has a luminosity of $10^4 L_\odot$
- H$^{13}$CN gives 400 $M_\odot$ for the rotating disk and of 1000 $M_\odot$ for the extended envelope