25: Formation of Massive Stars

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Reading

• Stahler & Palla, “The Formation of Stars”, §12.5 & §15.2-15.4
• Detailed reviews in PPIV and PPV
  – §2 of PPV includes chapters on the formation of massive stars, ultracompact HII regions, and the early lives of massive stars, and disks around young OB stars
  – PPV is available at:
    http://www.ifa.hawaii.edu/UHNAl/ppv.htm
Outline

• Low mass vs. high mass star formation
• Properties of massive stars and where they form
• Massive stars & clusters
• Association of massive stars and dense molecular gas
• Properties of ultracompact HII regions
• Winds & champagne flows
• Cores, disks & jets
Relation to Low Mass Star Formation

• The formation of a low mass star begins with the quasistatic contraction of a dense core as ambipolar diffusion removes magnetic support
  – As $B$ decreases, the core becomes magnetically supercritical
  – This marks the initial condition for dynamical collapse
• After becoming gravitationally unstable, the core undergoes a phase of free-fall, isothermal collapse
  – Ensuing major evolutionary stages include
    • Accretion
      – Presence of a central protostar and a circumstellar disk surrounded by an infalling envelope of dust and gas
    • Outflow (winds & jets)
      – The protostar deposits linear & angular momentum, and mechanical energy into its surroundings
  – Finally the star settles onto the ZAMS
Applicability to High Mass Stars

- Evolutionary time scales for high-mass stars are short
  - \( << \) for low-mass stars
  - Massive stars should modify their environment soon after a stellar core has formed since their Kelvin-Helmholtz time scale (\(< 10^4\) yrs for an O star) is short (\( \tau_{KH} = E/L \sim GM^2/LR \)) (Shu et al. 1987 AARA 25 23)

- Core H-burning begins before accretion of matter from the surrounding protostellar envelope stops
  - Disks & jets are less distinct than for low mass stars

- When the protostar reaches the ZAMS, it begins producing appreciable UV flux and (possibly) a strong wind modifying the surrounding conditions, structure & chemistry
  - The 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
Observational Challenge

• Difficult to determine physical conditions because of rapid evolution & observational disadvantages

• Massive stars are born deep in molecular cores
  • Star formation is obscured by the dust that surrounds them
  • Cannot be investigated at optical wavelengths
    – Traditionally poor angular resolution

• Massive stars are usually born in clusters or groups
  • Individual studies are usually afflicted by confusion

• Regions of massive star formation are rare (because massive stars are rare)
  – Regions of massive star formation are on average more distant than the sites of low-mass star formation
    • cf. Taurus-Auriga (150 pc) with Orion (450 pc)
Massive Stars are Hot Stars

• OB stars emit the bulk of their radiation at $\lambda < 912$ Å
  – Ionize the dense molecular gas producing C/UC HII regions
  – Dust surrounding ionized gas absorbs all the stellar radiation
    • Either directly or after being processed in the nebula
    • Produces compact regions of warm dust that reemit the absorbed energy in the far-IR

• The study of the environment around young massive stars should be performed through observations of ionized, atomic, & molecular gas at IR, mm, & radio where the interstellar opacity is low
  – Radio interferometers (VLA, OVRO, BIMA, IRAM) have opened up this field for investigation by providing
    • High angular resolution
    • Sensitivity
    • Spectral resolution
Radio Interferometers
The SMA

- Submillimeter array on Mauna Kea
  - Eight 6-m antennae
  - 300 µm - 1.7 mm
CARMA=BIMA+OVRO

- Cedar Flat
- Six 10.4-m telescopes
- Nine 6.1-m telescopes
- Configurations
  - A: 0.25-2 km
  - B: 0.1 -1 km
  - C: 30-350 m
  - D: 8-150 m
- Receivers
  - 115 GHz
  - 230 GHz
  - 345 GHz

D Array
(3.7 arc sec at 115 GHz)
ALMA

• ALMA = Atacama Large Millimeter Array
• Chilean Atacama Desert is one of the highest (16,000 ft) driest places on Earth, making it an ideal mm site
• 64 (?) x 12-m dishes
• Movable antennas
• Longest baselines ~ 14 km
  – 15 mas at 1 mm
• Construction complete by 2011
Molecular Cores & Massive Stars

• A key issue in star formation is the problem of initial conditions
  – Why are certain star-forming regions seeds for large-scale clusters, while others create stars in an isolated fashion (Taurus vs. Orion)?
  – Why do some cores form one star, while others give rise to binaries, triples, or even larger conglomerates?
  – What determines the star formation efficiency?
  – Is star formation bimodal?
  – What determines the initial mass function (IMF)?

• *Why do some clouds form massive stars?*
Questions Regarding Massive Stars

- What is the basic unit within a molecular cloud that will give birth to a massive star?
- What are the similarities between the formation of high & low mass stars?
  - Do massive stars have disks?
  - Do massive stars have a bipolar outflow phase?
- How is the environment around new massive stars affected by strong UV and winds?
- What is the connection between massive stars & masers
  - Are different maser species (H$_2$O, OH, SiO) signposts of different evolutionary stages?
- Are massive stars formed by accretion or by stellar mergers (Bonnell 1998 MNRAS 298 93)?
  - For dust opacity the Eddington luminosity limited mass is ~ 20-40 M$_\odot$ (Kahn 1974 A&A, 37, 149)
Properties of Massive Stars

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

<table>
<thead>
<tr>
<th>Spectral Type</th>
<th>Mass ($M_\odot$)</th>
<th>$M_V$</th>
<th>$T_{\text{eff}}$ (K)</th>
<th>$\log_{10} \left( \frac{Q}{\gamma \text{ s}^{-1}} \right)$</th>
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<td>O5</td>
<td>60</td>
<td>-5.6</td>
<td>48,000</td>
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<td>O8</td>
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<td>-5.2</td>
<td>33,500</td>
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<td>B0</td>
<td>18</td>
<td>-4.4</td>
<td>30,000</td>
<td>47.7</td>
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</table>
Properties of Massive Stars
Where Do Massive Stars Form?

- Massive stars in our Galaxy are born predominantly within the dense cores of giant molecular clouds
  - The Orion-Monoceros complex seen in CO is the nearest region of massive star formation, with a number of clusters of young stars associated with peaks in CO emission
  - Runaway O (10-15%) & B (2%) stars may arise from binary-binary interactions in the centers of dense systems (Clarke & Pringle 1992 MNRAS 255 432)
Star Clusters

• Stars do not form in isolation
  – Associations range from $N = 2 - 10^7$
  – Majority form in *T or OB associations*
    • 10% of Milky Way stars originate in open clusters (Adams & Myers 2001 ApJ 553 744)

• Intense star formation is concentrated in super star clusters (SSCs)
  – High resolution images show *starburst galaxies* host massive stellar clusters
SSCs in the Antennae Galaxies

- NGC 4038/4039 merger with ongoing star formation
  - Old red nuclei
  - Multiple blue SSCs
    - Sizes ~ 1–5 pc
    - Ages 5–100 Myr
      - 70% < 20 Myr
  - Dark (dusty) interaction region
    - Young (embedded) SSCs
    - Massive GMCs
    - Warm dust

Whitmore et al. 1999

3 kpc
A Spectrum of Stellar Clusters

Open clusters
mass: \(10^{3-5} M_\odot\)
loose, extended

Globular clusters
mass: \(10^{4.2-6.6} M_\odot\)
centrally concentrated

Bound objects that survive \(10^{10}\) yrs are called globulars even when they look like sparse open clusters.
Is Orion a Prototypical Massive Cluster?

- 450 pc
- \( t < 1-2 \) Myr
- 3500 stars within 2.5 pc radius
  - 0.1–50 M\(_\odot\) stars
  - 900 M\(_\odot\) total
- A few O stars
  - Low mass stars too (Hillenbrand 1997 AJ 113 1733)
Local Massive Clusters

~ 25 O5 stars
~ $10^{51}$ Ly$_c$ s$^{-1}$
~ 6 kpc, $A_V$ ~ 4.5 mag
~ 0.3 - 1 Myr
(Brandl et al. 1999)

~ 100 O5 stars ($2 \times 10^4$ M$_\odot$)
~ $4 \times 10^{51}$ Ly$_c$ s$^{-1}$
~ 50 kpc, $A_V$ ~ 1.2 mag
~ 2 - 4 Myr
(Walborn et al. 2002)
Natal Material: Clumps & Cores

- Star formation begins in dense cores of giant molecular clouds (GMCs)
- Structure of GMCs appear to be self-similar over a wide range of sizes & masses
  - Often described as consisting of clumps and cores
    - Clumps \( (n \approx 10^{5-6} \text{ cm}^{-3}, T \approx 16 \text{ K}, M \approx 10^{2-4} M_\odot) \) are where massive stars & cluster stars form
      - \( dN/dM \sim M^{-1.6} \) the most massive clumps contain most of the mass
    - These clumps provide the natal material for the formation of stellar clusters
  - Cores are substructure in clumps
    - Smaller, denser, and lower mass \( (\sim 10^2 \text{ } M_\odot) \) than clumps
    - Sites of star formation within clumps
Structure of Molecular Clouds

- CO maps show that molecular gas is inhomogeneous on all scales
Clumps

• Clumps can be identified within GMCs in $l-b-v$ space
  – Williams et al. analyzed the $^{13}$CO 1-0 clump structure of the Rosette and Maddalena Clouds
  – The Rosette is a site of active, massive star formation; Maddalena’s cloud is not
  – Clump masses derived using the X-factor
    • Calibrated with $^{13}$CO
Molecular Cores

- The study of star formation is intrinsically linked with the study of dense cores, the birthplace of stars
  - Progress has been made in the last few decades, since the radio astronomy made it possible to probe these dense regions in molecular clouds
  - Important tracers are CS and NH$_3$
- Cloud core properties serve as the initial conditions that likely determine the characteristics of the star(s) that form within them
  - Benson & Myers 1989 ApJS 71 743
  - Jijina et al. 1999 ApJS 125 161
Molecular Cloud Cores


Fig. 1a — Half-maximum intensity contours of 16 dense cores in dark clouds, in the 1.3 cm \((J, K) = (1,1)\) lines of \(\text{NH}_3\), from Benson & Myers (1989), and in the 3.0 mm \(J = 2 \rightarrow 1\) line of CS, and the 2.7 mm \(J = 1 \rightarrow 0\) line of \(^{13}\text{CO}\), from Fuller (1989). For each map, North is up, East is left, and the linear scale 0.2 pc is indicated. A cross indicates an associated star.
Molecular Cloud Cores

- Typically < 10% of the area of a GMCs is detected in dense gas tracers such as CS or NH$_3$
  - Typical molecular gas is defined as that traced by $^{12}$CO 1-0
    - Volume-average density $\approx$ 50-100 cm$^{-3}$
    - Average local density $\approx$ 4-12 x 10$^3$ cm$^{-3}$
  - Dense gas is nonuniformly distributed through the cloud within numerous discrete and localized cores

- The first stage of star formation starts from a process of contraction of molecular cloud cores

- Observations of the NH$_3$ $J$=1, $K$=1
  - Cold (kinetic temperature ($T_K \approx 10$ K) dense ($n_H \approx 10^4$ cm$^{-3}$) condensations
  - Size 0.1 pc (20,000 AU)
  - Masses of a few M$_\odot$ to 10$^2$ M$_\odot$
    - 20% of the total gas in GMCs is in massive cores
    - Conditions inferred depend on what molecular tracer is used because critical densities span a large range
## Dense Gas Tracers

<table>
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<tr>
<th>Molecule</th>
<th>Transitions</th>
<th>Frequency (GHz)</th>
<th>E/k (K)</th>
<th>$n_{\text{crit}}$ (cm$^{-3}$) @ 10 K</th>
<th>$n_{\text{eff}}$ (cm$^{-3}$) @ 10 K</th>
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<td>CS</td>
<td>1-0</td>
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<td>4.6 x 10$^4$</td>
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<td>2-1</td>
<td>98.0</td>
<td>7.1</td>
<td>3.0 x 10$^5$</td>
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<td>3-2</td>
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<td>1.7 x 10$^5$</td>
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<td>2.1 x 10$^4$</td>
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</table>
Jijina et al. NH$_3$ (1,1) & (2,2) Core Survey
Jijina et al. NH$_3$ Core Survey

![Graphs showing distributions of parameters such as $\Delta v_{\text{int}}$, $T_{\text{kin}}$, and $\nabla v_{\text{lsr}}$.]
Jijina et al. NH$_3$ Core Survey

![Histograms of $\log_{10}(M_{\text{vir}}/M_\odot)$ for different categories: all, IRAS, no IRAS, cluster, and no cluster.]
Jijina et al. NH$_3$ Core Survey

• The presence of cluster associations has a dramatic effect on core gas and YSO properties
  – Line widths, kinetic temperatures, and core sizes for cores in clusters are much larger than the corresponding physical properties of cores in isolated star-forming environments
  – The luminosities of YSOs embedded in cores associated with clusters are much higher than for those in isolated environments

• There are strong regional trends in properties
  – Cores in Taurus are smaller, less turbulent, cooler, and have a higher virial abundance of NH$_3$, while cores in Orion are larger, hotter, have large nonthermal line widths, and have a low virial NH$_3$ abundance
  – Cores with IRAS sources are also bigger, more turbulent, and hotter than those with none, but this effect is less marked
Mid-IR Dark Clouds = HMSC?

- IR dark clouds are optically thick at 8 µm (Sridharan et al. 2005 ApJL 634 57)
  - Starless cores are less turbulent & cooler
Cores & UC HII Regions

- NH$_3$ emission in the (1,1) and (2,2) inversion transitions is commonly (~70%) detected towards compact HII regions (Churchwell et al. 1990)
  - Cores associated with regions of recent massive star formation have
    - Sizes of 0.3-1.0 pc
    - $T_K \sim 30$-50 K
    - $n_{H_2} \sim 2 \times 10^4$ - 3 x $10^6$ cm$^{-3}$
    - $M \sim 10^3$ - 10$^4$ M$_\odot$
    - Line widths are largely turbulent with thermal contributions of only ~ 0.3 km/s
  - NH$_3$ (1,1) through (5,5) probe progressively warmer, denser gas
    - Are physical conditions are assumed representative of a phase prior to the formation of an OB cluster?
      - Massive cores associated with embedded YSOs are indistinguishable from massive starless cores (Caselli & Myers 1995 ApJ 446 665)
Hot Molecular Cores

• **Hot cores** are defined observationally as
  – Compact \((d < 0.1 \text{ pc})\), dense \((n_{H_2} > 10^7 \text{ cm}^{-3})\) & warm \((T > 100 \text{ K})\)

• CS (7-6) observations towards a large sample of star forming regions with \(H_2O\) masers show a \(~ 60\%\) detection rate (Plume et al. 1992)
  – \(n_{CRIT} \sim 2 \times 10^7 \text{ cm}^{-3}\)
  – Single dish observations of excited \(NH_3\) indicates the presence of hot molecular gas, (Cesaroni, Walmsley, & Churchwell 1992)

• \(NH_3\) (4,4) interferometer data (1” beam) shows
  – Hot \((T \sim 50 \text{ K})\) dense \((>10^5 \text{ cm}^{-3})\) molecular gas localized in small \(<0.1 \text{ pc}\) structures with masses \(10 - 10^2 M_\odot\) (Cesaroni et al. 1998 AA 331 709)
G34.3+0.15

- Massive star-forming region G34.3+0.15
- Top left: NH$_3$(1, 1) at 2.\'2 resolution (Heaton et al. 1985)
- Top right: HCO$^+$(1-0) at 6\'' resolution (Carral & Welch 1992)
- Bottom right: NH$_3$ (3, 3) at 1\" resolution (Heaton et al. 1989)
  - Dashed contour is the lowest level of the 15 GHz continuum from the bright cometary H II region
  - Imaging of the stellar population is missing!
Association of UCHII & Hot NH$_3$ Cores

- Hot NH$_3$ cores are invariably located near and in most cases intimately associated with UC/C HII regions
  - NH$_3$ (solid contours)
  - Radio continuum (gray in the top & middle panels & dashed contours in the bottom)
    - *Top*: G10.47+0.03 & *Middle*: G29.96-0.02 (Cesaroni et al. 1998)
    - *Bottom*: G61.48+0.09 (Gómez et al. 1995)
  - Not all compact HII regions are associated with hot, dense NH$_3$ clumps
    - NH$_3$ gas may have been disrupted by the expansion of the HII region and/or outflows
Signposts of Young, Massive Stars

- Compact HII regions, intimately associated with warm and dense regions of molecular gas is the hallmark of newly formed massive stars
- E.g., G9.62+0.19
  - UC HII region
  - NH$_3$ hot core (dashed)
  - 1.3 cm continuum emission (solid)
  - $\text{H}_2\text{O (▲)}$ & OH (□) masers (Kurtz PPIV)
Association of Dense Gas & Massive Stars

- **G29.96-0.02:**
  - High density clumps with embedded hot molecular cores
    - $^{34}\text{S}\ J=5-4$ (gray)
    - $\text{CH}_3\text{CN}\ J=6-5$ (acetonitrile) hot core (black)
    - UC HII region 1.3 cm radio continuum emission (dotted)
  - Bottom enlargement shows $\text{H}_2\text{O}$ masers ($\triangle$) (Kurtz, PPIV)
Compact HII Regions

- Young, massive stars emit copious Ly continuum photons
- Excite their surroundings, giving rise to small, dense HII regions
  - Sketch of UC HII region G 5.89-0.39 embedded in a dense cold cloud
  - UV from the new O5V star creates an HII region and a dust-free cavity in the parental molecular cloud
  - Outflow from central star
SED of UC HII Regions

- Compact HII regions have high emission measures that makes them bright IR & radio sources
Ionized Gas in UC HII Regions

- 10-20% of HII regions are classified as C/UC HII
- UC HII regions are powerful radio beacons of newly formed stars still embedded in their natal molecular clouds
  - Physical parameters of compact regions of ionized gas are determined mostly from radio data
    - Radio continuum is modeled as free-free from an isothermal homogeneous region of ionized gas
    - $T_e$ and $EM = \int n_e^2 \, dl$ are determined from the optically thick and thin portions of the spectrum, respectively
- If the geometry & distance are known
  - Allows a determination of the rms electron density
  - $T_e$ can also be determined from radio recombination lines
- Complete surveys are possible, e.g., by combining VLA/MSX (Giveon 2005, AJ, 129, 348)
Properties of UC HII Regions

• HII regions around recently formed massive stars have
  – Diameters $D \sim 0.005 - 0.5$ pc
  – $n_{\text{H}_2} \sim 2 \times 10^3 - 3 \times 10^5$ cm$^{-3}$
  – $EM \sim 2 \times 10^6 - 1 \times 10^9$ pc cm$^{-6}$

• The physical properties of UC HII regions are strongly correlated
UC HII Regions Correlations

• Relationship between physical parameters of C/UC HII regions
  – Circles: Garay et al. 1993
  – Pentagons: Gaume et al. 1995
UC HII Regions Correlations

• Power law fits give
  – \( n_e \sim D^{-1} \)
  – \( EM \sim D^{-1.5} \)

• \( EM \sim n_e^2 D \) these two relations are not independent
  – For a Stromgren sphere \( n_e^2D^3 = \text{const.} \) : 
    \[
    n_e \sim D^{-3/2}
    \]
    if the distribution of stellar masses is independent of the initial conditions of the surrounding medium

• The shallow slope of the \((n_e, D)\) relation may occur because UC HII (< 0.05 pc) regions are systematically excited by lower luminosity stars than CH II (0.05 < \( D/\text{pc} \) < 0.5)
Ionization of Compact HII Regions

- UCHII regions are excited by less luminous stars than those exciting compact HII regions
  - Some UCHII regions may be externally ionized
    - Dense blobs in a larger, inhomogeneous HII region excited by a single O star
    - $N_u$ required to excite such an UCHII is smaller than that emitted by the star by $\Omega/4\pi$, where $\Omega$ is the solid angle subtended by the UC clump from the star
  - Shallow power-law may reflect significant Lyc dust absorption in with UC HII
Morphology of Compact HII Regions

• High angular resolution radio continuum observations show a variety of morphologies
  – *Shell* source G45.07+0.13 (Turner & Matthews 1984)
  – *Bipolar* source NGC 7538 IRS1 (Campbell 1984).
  – *Cometary* source G34.3+0.15 (Gaume et al. 1994)

• Interferometer maps have missing flux!
Wood & Churchwell (1989 ApJS 69 831) identified distinct morphologies in a VLA radio continuum survey (but see dePree et al. 2005 ApJL 624 101 where 30% are cometary & core-halo is dropped)
Kinematics of Compact HII Regions

• Kinematics may be shaped by:
  – Density structure of the ambient medium and its response to
    • Expansion of ionization fronts and stellar winds
  – By the motion of the exciting star
    • Kinematics of compact HII regions can derived from radio recombination lines
  – UCHII regions (< 0.01 pc) with broad lines are known as hypercompact HII regions (HCHII)
    • $\Delta V \approx 40$-50 km/s and ranging up to 100 km/s
Global Motions

• Integrated line profiles provide information about the global properties of the motions
  – Broadening of a line with principal quantum number $n_U$ includes
    • Thermal broadening
      $$\Delta v_{\text{th}} = 2 \left( 2 \ln 2 \frac{kT_e}{m_H} \right)^{1/2} \approx 21.4 \left( \frac{T_e}{10^4 \text{ K}} \right)^{1/2} \text{ km/s}$$
    • Broadening by electron impact
      $$\Delta v_i = 4.2 \left( \frac{n_U}{100} \right)^{7.4} \left( \frac{T_e}{10^4 \text{ K}} \right)^{-0.1} \left( \frac{n_e}{10^4 \text{ cm}^{-3}} \right) \text{ km/s}$$
    • Non-thermal broadening $\Delta v_{\text{nt}}$
      – Blending of emission, within an observing beam, from gas at different flow velocities (microturbulence) or large scale velocity fields (macroturbulence)
    • In general, the line profile is a Voigt function
      – Neglect of pressure broadening for $n_U < 100$
      – The line profile is roughly Gaussian with
        $$\Delta v_{\text{obs}}^2 = \Delta v_{\text{th}}^2 + \Delta v_i^2 + \Delta v_{\text{nt}}^2$$
Regular & Compact HII Regions

- Radio recombination lines from compact HII regions are distinct from larger HII regions
  - Line widths of compact HII regions are broader than those of diffuse HII regions
  - Compact & ultracompact HII regions (stars), typical (squares) and extended (triangles) HII regions
Origin of Line Widths

• The thermal & pressure broadening widths are computed using $T_e$ from radio recombination lines and $n_e$ from the radio continuum
  – “Non-thermal” width is what’s left over after subtracting other components
  – $\Delta v_{nt}$ is the biggest contribution to line width in compact HII regions

• Non-thermal widths in compact and UC HII regions may be due to large scale systematic gas motions or turbulence
  – Expansion of small, dense clumps into less dense environment
  – Champagne flows
  – Stellar winds
    • $\Delta v_{nt}$ decreases as the size increases—trend is not understood
Photoevaporating Disks?

• Photoevaporating disks?
  – In a photoevaporated circumstellar disk the line width at small radii reflects rotation & expansion of ionized gas
  – At larger distance velocities only reflect expansion
  – Mass loading from clumps embedded within UC HII regions may also contribute

• Photoevaporated clumps fed into the flow may increase line widths
  – Since the amount of HII incorporated is proportional to the number of ionizing photons, the observed trend could be due to the geometric dilution of the ionizing photons with distance
Internal Motions of Bipolar CHII

- Compact HII regions with bipolar radio continuum morphologies have been found in a handful of cases
  - NGC7538-IRS1, NGC6334(A), G45.48+0.13 and W49A-A
    - The core of NGC7538-IRS1 (HCHII) shows a double radio lobe structure, with lobes separated by 600 AU
    - NGC6334(A) has a bright compact central region, having a shell appearance, and extended symmetrical lobes of lower brightness

- Ionized gas may be confined by a flattened structure of neutral gas & dust
  - Radio recombination line observations of bipolar HII regions show steep velocity gradients along their symmetry axis
  - The morphology and kinematics suggest that the ionized gas is undergoing a high velocity outflow
CHII Region K3-50A

- The morphology of K3-50A is highly elongated
  - H76$\alpha$ line ~ 100 km/s wide
  - The H76$\alpha$ line center shifts by 60 km/s over 0.4 pc (150 km/s/pc) along the major axis of (De Pree et al. 1994 ApJ 428 670)
• NGC7538-IRS1 shows a double radio lobe structure, with lobes separated by 600 AU
NGC 7538 IRS1

• Largest mass motions of ionized gas known are observed toward the core of the NGC7538-IRS1 HCHII region
  – Extremely wide H66α line profiles
  – FWHM ~ 180 km/s (Gaume et al. 1995 ApJ 438 776)
  – Motions may trace a stellar wind outflow and photoevaporation of nearby clumpy neutral material
• NGC 7538-IRS1 provides evidence for the presence of collimated ionized bipolar outflows
  – May imply that massive disks, which could collimate the wind, are formed during the process of collapse of massive stars
Expansion of HII Regions

• Due to the pressure difference in between HII and the surrounding neutral gas, HII regions will expand into the ambient medium
  – Classical analysis of the expansion assumes a homogeneous ambient medium and neglects stellar winds (cf. Spitzer 1978; Dyson & Williams 1980)

• Classical expansion is characterized by two main phases
  – Initially when the young massive star embedded in a molecular cloud produces UV photons, an ionization front is formed which moves rapidly outward through the ambient medium
  – This phase of expansion comes to an end when the number of photoionizations within the ionized region equals the number of recombinations
Expansion of UC HII Regions

• Measured the angular expansion of the shell-like UC HII region W3(OH) implies a speed of \( \sim 35 \) km/s dynamical age of \( \sim 2300 \) years
  – Difference map of W3(OH) with a time baseline of 9.3 yr
  – The 15 GHz (gray scale)
  – Difference map (contour)
    • Top: observed difference map
    • Bottom: difference map generated from subtracting the 1986 image from a simulated self-similar expansion of the 1986 data

• Best fit model is a slowly expanding shell-like H II region
  – Inconsistent with a freely expanding shell or a bow shock
Young Dynamical Ages?

- The angular expansion rate of the shell-like UC HII region G5.89-0.39 yields a dynamical age of \( \sim 600 \text{ yr} \) \( L_W \sim 3 \times 10^{36} \) erg/s for the O6 star
  - \( n_0 \sim 10^7 - 10^8 \text{ cm}^{-3} \)
- The observed shell radius and expansion velocity can be explained by the simple stellar wind model if the nebula is very young \( \sim 500 \text{ yr} \)
  - Consistent with dynamical age
Expansion of HII Regions

- An HII region fills a region with a radius, $R_S^0$ called the Strömgren radius

$$R_S^0 = 0.032 \left( \frac{N_U}{10^{49} \text{ s}^{-1}} \right)^{1/3} \left( \frac{n_0}{10^5 \text{ cm}^{-3}} \right)^{-2/3} \text{ pc}$$

$n_0$ is the initial density of the ionized gas ($2 n_{H2}$), where is the molecular density of the ambient gas

$N_U$ is the rate of ionizing photons emitted by the exciting star

$A_{216}$
Initial Expansion of HII Regions

- This initial phase is rapid and short lived
  - The characteristic time, $t_S$, in which the Strömgren radius is reached is
    \[
    t_S = \frac{1}{n_0 \alpha_B}
    \]
    
    $\alpha_B$ is the recombination coefficient excluding captures to the ground level

- For an O7 ZAMS star $N_U = 4 \times 10^{48}$ s\(^{-1}\)
  - In a medium with $n_0 = 10^5$ cm\(^{-3}\), the Strömgren radius, of 0.015 pc, is reached in $\sim$ one year
  - This should be taken only as a nominal value
  - It is likely that the star turns on its UV output over a considerably longer interval
Subsequent Expansion

• Hot HII expands driving a shock front into the HI/H$_2$
  – The expansion of the HII region during this phase is set the interaction between the ionization and shock fronts
  – The radius, $R_i$, of the HII region increases with time as

$$R_i = R^0_S \left(1 + \frac{7c_{\text{HII}} t}{4R^0_S}\right)^{4/7}$$

(cf. Spitzer 1978) where $c_{\text{HII}}$ is the sound speed in ionized gas
Subsequent Expansion

• Expansion stalls when the hot, low density HII reaches pressure equilibrium with the surrounding cool medium
  – The final equilibrium radius of the HII region

  \[ R_f = \left( \frac{2T_e}{T_0} \right)^{2/3} R_s \]

  where \( T_0 \) is the ambient temperature
  – Using the Strömgren relation the equilibrium radius is
Subsequent Expansion

- This size is reached in a time

\[ t_{eq} \approx 7.6 \times 10^5 \left( \frac{N_U}{10^{49} \text{ s}^{-1}} \right)^{1/3} \left( \frac{n_0}{10^5 \text{ cm}^{-3}} \right)^{-2/3} \]

\[ \left( \frac{T_0}{100 \text{K}} \right)^{-7/6} \left( \frac{T_e}{10^4 \text{K}} \right)^{2/3} \text{ yr} \]

The result is approximate because the pressure of the ambient gas has been neglected in the derivation of the expansion law.
Stellar Winds

• OB stars have strong stellar winds
• The kinematics of UCHII regions may be dominated by the wind energy & momentum
  – Winds have been proposed as the mechanism for producing shell morphologies of UC HII regions (Castor, McCray, & Weaver 1975; Shull 1980)
• It is unknown when winds begin in OB stars
  – Before stellar winds begin bipolar outflows produced in the formation process may be a major input of mechanical energy and momentum
Spherical Stellar Wind Models

- An UC HII region is surrounded by the dense, ambient molecular gas that provides the thermal pressure required for confinement.

- Infalling ambient molecular gas creates both an increase in density and pressure at the ionized front of the UC HII region.
Stellar Winds

• If stellar winds are important from the start of the compact HII region phase evolution might proceeds as follows
  – Interaction of the wind with the ISM produces a dense shell of circumstellar gas that expands away from the star
    • This shell is exposed to the UV from the new OB star, thus it will be either totally or partially ionized
    • Evolution of the HII region is closely tied to the evolution of the circumstellar shell
Stellar Winds

- When the shell is driven by the pressure of the hot bubble of shocked stellar wind, the expansion law is (Castor et al. 1975 ApJL 200 107)

\[ R_{sh} \approx 0.042 \left( \frac{L_W}{10^{36} \text{ erg s}^{-1}} \right)^{1/5} \left( \frac{n_0}{10^5 \text{ cm}^{-3}} \right)^{-1/5} \left( \frac{t}{10^3 \text{ yr}} \right)^{3/5} \text{ pc} \]

- \( L_W \) is the wind mechanical luminosity

- The expansion velocity is

\[ V_{sh} \approx 24.7 \left( \frac{L_W}{10^{36} \text{ erg s}^{-1}} \right)^{1/5} \left( \frac{n_0}{10^5 \text{ cm}^{-3}} \right)^{-1/5} \left( \frac{t}{10^3 \text{ yr}} \right)^{-2/5} \text{ km/s} \]
Importance of the Wind

• Under what conditions is the wind dynamically more important than the classical expansion due to the difference in pressure between the ionized gas and ambient medium?
  – Shull (1980) shows that the wind is more important when

\[
\left( \frac{L_W}{10^{36} \text{ erg s}^{-1}} \right) > 0.33 \left( \frac{N_U}{10^{49} \text{ s}^{-1}} \right)^{2/3} \left( \frac{n_0}{10^5 \text{ cm}^{-3}} \right)^{-1/3}
\]

  – Observational data to test this are not yet available due to the difficulty of deriving \( L_W \)
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
Champagne Flows

- Champagne flow gives rise to an HII region that expands supersonically away from the high density region
  - Two main phases of HII region evolution
  - The ionization front rushes rapidly into the ambient medium
    - If $\rho$ falls faster than $r^{-3/2}$ the I-front is not trapped and the whole zone facing the low density region is ionized
  - The pressure gradient left behind by the I-front produces a strong shock which moves supersonically into the ionized low density medium
    - Ionized gas begins to stream away toward the direction of decreasing density

Tenorio-Tagle (1979 AA 71 59)

Fig. 1 a—d. The evolution of an H II region
Champagne Flows

(Yorke, Tenorio-Tagle, & Bodenheimer 1984)

Figure 3  (a) Isodensity contour lines and velocity arrows in the meridional plane show the champagne flow in cylindrical symmetry at $t = 6.6 \times 10^5$ yr after an O star ($7.6 \times 10^{44}$ Ly photons s$^{-1}$) turns on inside of a molecular cloud about one Strömgren radius from its edge. Contour levels are labeled with values for $\log \rho$ (cgs units); the H II region boundary is given by the dashed-dotted line. Arrows show the magnitude and direction of the gas velocity at selected points (tips of arrows); the velocity scale for an arrow of unit length is given in the lower right corner. The triangle denotes the position of the ionizing source. Crosses mark the positions of Lagrangian tracers originally at the cloud’s edge. (b) The calculated radio map at $\lambda = 11$ cm of the champagne blister displayed in (a) is shown as seen by an “observer” in the equatorial plane. The projected position of the star is indicated by the cross. Contour levels are labeled by the surface brightness in units $f_0 = 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ Hz$^{-1}$. The assumed beam size is indicated at the lower right. Contour levels are spaced linearly close to the star and logarithmically for levels less than $f_0$ [from Yorke et al. (202)].
Champagne Flows

• Hydro simulations show that a blister type HII region results
• Ionization bounded on the high density side and density bounded on the side of outward champagne flow
  – The HII region is fan shaped
  – Numerical calculations of the kinematics show that HII is accelerated away from the molecular cloud up to several times $c_{\text{HII}}$ (Yorke, Tenorio-Tagle, & Bodenheimer 1984 AA 127 313)
  – Velocity increases with distance from the cloud, up to ~ 30 km/s
  – The average velocity of the HII gas is shifted by a small amount (5 km/s) with respect to the molecular cloud
G32.9+0.19: A Champagne Flow?

- H 92 $\alpha$ shows a fan-shaped HII region with a velocity gradient running along of the symmetry axis of cometary-like structure
- Velocity increases smoothly from the head leading edge to the tail by $\sim 10$ km/s
- The observed velocity fields and morphologies are in good agreement with those predicted by the champagne model
  - Similar HII/CO velocities at the head position suggests a champagne flow
W3 (OH) as a Champagne Flow

- Compact HII region W3(OH) has a
  - 12 km/s velocity gradient
  - Weak radio continuum emission feature aligned with the velocity gradient & extending away from the high density gas immediately around the newly formed star
- Suggests that the W3(OH) HII region is undergoing a supersonic champagne flow
  - Consistent with proper motion measurement?

Top: 18 cm continuum
Bottom: Intensity weighted average velocity from H92 α. Velocity ranges from -44 in the E to -62 km/s in the W. 3 km/s contour interval
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 may explain details of the morphology
    - Limb brightening
    - Emission pinches back down to the symmetry axis
      - Not easily explained by champagne models
Bow Shocks

- The characteristic size of a cometary HII region in the bow shock model given by the location of the terminal wind shock occurs
  - This distance is where the momentum flux in the wind equals the ram pressure of the ambient medium is

\[
l_{BS} = 0.015 \left( \frac{\dot{M}_*}{10^{-6} M_\odot \text{ yr}^{-1}} \right)^{1/2} \left( \frac{v_w}{10^3 \text{ km s}^{-1}} \right)^{1/2} \left( \frac{n_0}{10^5 \text{ cm}^{-3}} \right)^{-1/2} \left( \frac{v_*}{10^3 \text{ km s}^{-1}} \right)^{-1} \text{ pc}
\]
Champagne Flows vs. Bow Shocks

- Both the champagne & bow shock models reproduce the morphology of cometary HII regions
- Kinematics and lifetimes differ between models
  - Bow shock model predicts velocity gradient should be steeper in the head than in the tail
  - Champagne model predict the largest gradients are expected in the tail, where the gas is accelerated out the nozzle
  - Contrary to the champagne flow, the bow shock predicts that the lines should be broader along the leading edge of the ionization front than they are behind
  - In the champagne flow the HII at the head of the cometary structure should be at rest with respect to the molecular gas while the bow shock model predicts it should be moving with the velocity of the star
G12.21-0.10

• High resolution map of CS 2-1 emission (contours) tracing dense molecular gas ahead of the cometary UCHII region G12.21-0.10
  – Radio continuum image (grey-scale)
  – + mark H$_2$O masers
G29.96-0.02

- **Left**: Observations of G29.96-0.02 (Wood & Churchwell 1991). **Right**: VanBuren & MacLow's (1992) bow shock model. The PV diagram is for a slit placed along the symmetry axis.
Bow Shock Models for Cometary HII Regions

• Cometary HII regions for which the observations seem to be best explained by a bow shock model are
• Champagne flows have also been proposed to explain G29.96-0.02 (Fey et al. 1995; Lumsden & Hoare 1996)
  – Contradictory results reflect the difficulty in discriminating between models!
Age & Evolutionary Status

• Regions of ionized gas formed in a medium of constant density expand into the ambient gas at $\sim c_{\text{HII}}$ until pressure equilibrium is reached
  – If HII regions are smaller than equilibrium radii $R_f$ their sizes indicate their ages
    • A HII region excited by an O7 star in a medium with $10^5 \text{ cm}^{-3}$ expands to $R_i = 0.1 \text{ pc}$ pc in 20,000 years
    • Small sizes of the UC HII regions (0.05 pc) implies that they are young
    • Lifetimes < 5000 years
Statistics of UCHII 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 $<M_{OB}> 23$ M$_\odot$ implies $\sim 0.04$ O stars yr$^{-1}$
  - 10 times smaller than that derived from UC HII regions
Statistics of UCHII Regions

• Why do we see so many UC HII regions?
  – The IRAS UC HII catalog may be contaminated
  – 65% of diffuse HII regions in a large (462) sample have IRAS colors that satisfy the Wood & Churchwell selection criterion (Codella, Felli, & Natale 1994)
  • Source confusion in the IRAS point source catalog?
Ages of UC HII Regions

• Hollenbach et al. (1994 ApJ 428 654) proposed that newly formed OB stars are surrounded by a massive primordial disk
  – The disk is photoevaporated by the UV photons from the star
  – Dense gas ionized close to the star flows away giving rise to the observed UC HII region
  – The reservoir of gas in the disks may last for $>10^6$ yr, depending on the mass of the disk

• UC HII regions could live much longer than their dynamical ages because they are constantly being replenished by a dense circumstellar reservoir
Photoevaporating Disks

Weak stellar wind

Strong stellar wind

\[ r_g = \frac{GM_*}{c^2} \]

Externally Photoevaporated Disks

+ A molecular cloud contains a star+disk accreting material
+ Left: temperature
+ Right: density & velocity
+ At $t=0$ $T < 100$ K (black)
+ The O star turns on at $t=0$, an I-front enters from the top. At the same time the O star's FUV radiation begins to heat the material at the surface of the disk. The I-front encounters the expanding disk material and is stopped here. It begins to wrap itself around the star+disk configuration.
+ Zoom into the central portions at $t=100$ yr and increase the frame rate
+ White contours are steps of temperature (x10) & density (x100)
Ages of UCHII

• Several authors have argued that the dynamical time scale does not give the age because the primordial ambient medium is clumpy

  – Mass loading due to the ablation of clumps could result in long-lived UC HII regions
  – Mass injection from photoevaporated globules into a stellar wind causes trapping of the ionization front resulting in compact (0.1 pc) long-lived ($10^5$ yrs) HII regions
Photoevaporating Columns in M16
Lifetime of UC HII Regions

- A simple explanation invokes a denser & warmer ambient medium than previously believed
  - Results in very small equilibrium radii
- Recent observations show temperatures and densities of the molecular gas around UC HII regions are \( \sim 100 \) K and \( 10^7 \) cm\(^{-3}\)
  - Under these conditions, the equilibrium radius of a region of ionized gas excited by an O9 star \( (N_U = 1.2 \times 10^{48} \text{ s}) \) is \( \sim 0.02 \) pc and the time to reach pressure equilibrium is \( \sim 10,000 \) yr
- UC HII regions could have already reached the equilibrium radius and are much older than the dynamical age
  - A large fraction of UC HII regions are excited by stars later than O9 and therefore should have smaller equilibrium radii
Outflows and Accretion Disks

• If massive stars form by accretion then precursors of UCHII regions must exhibit a period of rapid accretion accompanied by an equatorial accretion disk and a massive bipolar outflow
  – Accretion disks in massive star formation regions are difficult to detect because of
    • Large distances
    • Brightness of the central protostar
    • Difficulty of distinguishing a disk from the natal hot core, which is bright and may have large non-Keplerian velocity gradients
Molecular Outflows

• Molecular outflows have been observed toward numerous massive star formation regions
  – The molecular outflows from massive protostars have very large
    • Masses
    • Mass fluxes
    • Momenta
  – Mechanical luminosities
  – There is a correlation between the outflow mass flux and bolometric luminosity of protostars that holds over at least six orders of magnitude in luminosity
Molecular Outflows

Molecular Outflows

- Continuity of the $L - dM/dt$ relation may indicate that the formation of massive stars is simply an extension of the process of low-mass star formation to more massive stars
  - Seems unlikely for several reasons
    - Luminosity reflects the mass of the protostar
    - Mass determines the gravitational potential
    - Mass governs the rate of accretion
  - It is not surprising that a continuous $L - dM/dt$ relationship holds for a large range of luminosities!

- The correlation may have nothing to do with the process of star formation but may simply reflect the central role of gravity
Molecular Outflows

• Molecular outflows from massive protostars although similar to those from low mass stars are not as well collimated
  – There is no general theory for how 10-100 M\(_{\odot}\) of cold molecular gas can be accelerated and collimated on short timescales while matter is simultaneously rapidly accreted
    • X-winds invokes magnetic fields to redirect and collimate outflows
    • Developed for low-mass protostars that involve small masses
    • Probably is not applicable to massive outflows
Disks?

• Evidence for accretion disks around massive protostars exists for only a very few objects
  – Protostars with detected accretion disks have masses ranging from $10-370 \, M_\odot$ & radii from 500-10,000 AU
  – All have observed outflows
  – High resolution observations of CH$_3$OH masers have been interpreted as originating in accretion disks
  – Controversial
Outflows in G192.16-3.82

a): 12-m CO(1-0) molecular clump emission ± 1.3 km/s of $v_{LSR}$. A dot marks the 3 mm continuum source

b): 12-m map of the red (thick lines) and blue-shifted (thin lines) emission from 10.9 to 7.0 km/s and 4.4 to 0.5 km/s, respectively

c): OVRO image shows redshifted (thick lines) and blueshifted (thin lines) CO emission
Disk in G192.16-3.82

- **Left:** 7 mm continuum emission with data from the VLA
- **Right:** 7 mm VLA A array + VLBA's Pie Town antenna
  - Evidence for a solar-system sized “disk” around a 8-10 M\(_\odot\) massive protostar
## Young Massive Objects with Disks & Molecular Outflows

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