The Great Observatories:
Star Formation and the Interstellar Medium

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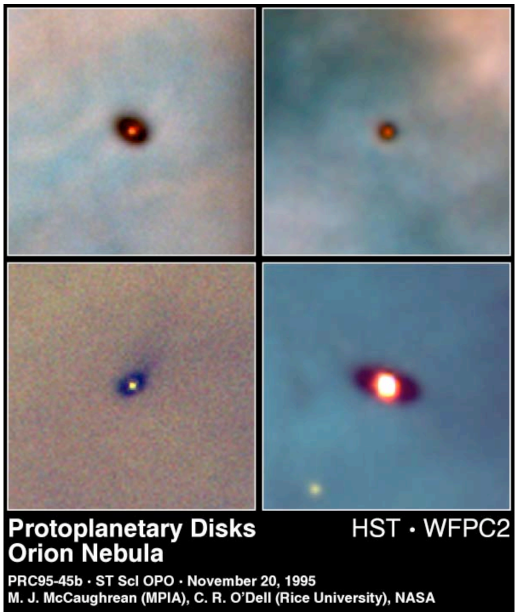
Symposium
Making the Most of the Great Observatories
Pasadena May 22-24, 2006

Star & Planet Formation:
A major goal of the 21st Century

- Star Formation
  - We have a broad-brush understanding of low-mass star formation
    - Cold (~15K), molecular, starless cores (SCs)
      Initial conditions? Initiation of collapse? Physical properties?
    - Collapse & formation of protostar (still a mystery) accompanied by
      - Accretion disk formation, don't know detailed properties and kinematics
      - Bipolar outflows (jets), but don't know how they are driven, or kinematics
      - Role of mergers? Mag fields? Composition? Turbulence?
    - Details Missing
    - What controls the IMF? Why so many low mass stars for every massive star
    - Why is SF/unit mass ~constant? (L_{IR} vs M_{mol})
  - For massive stars, even a broad-brush understanding is debatable
- ISM
  - Impact of star formation on the ambient ISM (feedback)
    - Evolution and structure of nebulae & bubbles
  - Again details not missing

Disk Silhouettes in Orion

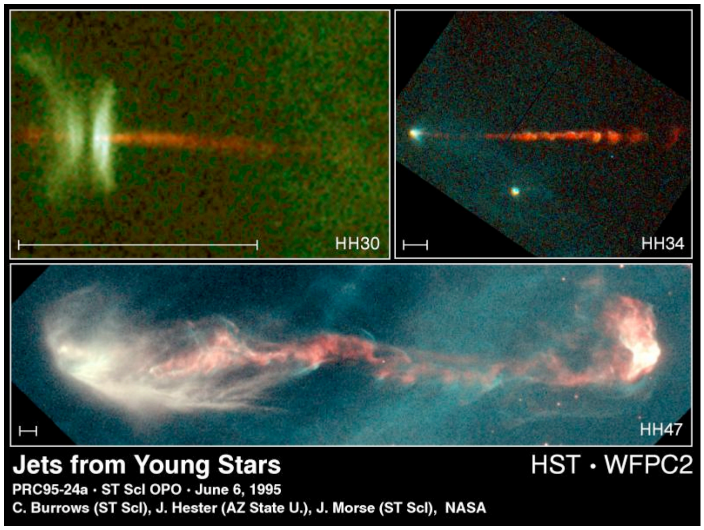


Edge-on disk in Orion

Optical Jets: Low Mass Protostars

Scattered Light Disk Plus a Bipolar jet D=450 ly

Jets are not continuous Accretion & Outflow are sporadic D=1500ly

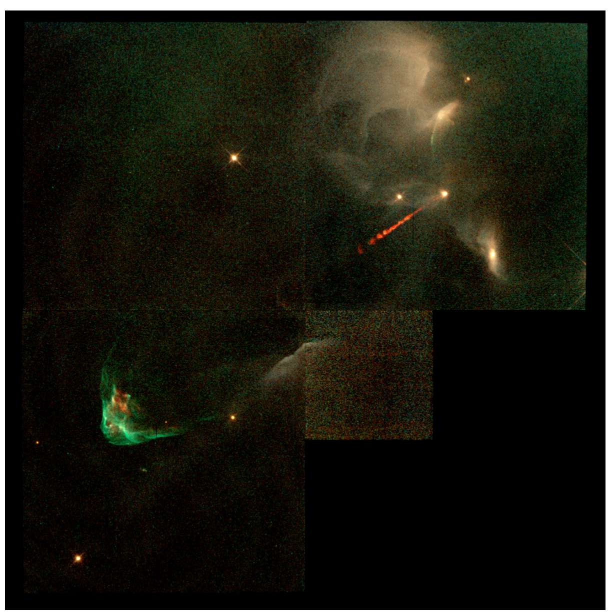


Jets may Precess & Interact with the ISM D=1500 ly

Lower left Bar=1000AU

HH34: Jets can be very large

Extent~1pc



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Synthesis of Survey on Important Problems in Star Formation

- First Stars
  - Formation at z=0?; Properties of Pop III stars?; How much must z change to permit the full range of stellar masses?
- Star Formation in Other Galaxies
  - Super star clusters (SSCs): Examples of young globular clusters? Formaiton? Effects on environment? Dynamical evolution? Natal molecular cloud properties?
  - Connections of MSF, SSCs, globular clusters, black holes to AGNs & Gal. nuclei
  - The starburst phenomenon: What drives them? What are their IMFs? Relation to MSFRs in the MW, especially those in the Galactic center?
  - How do stars in galactic nuclei form?
- Natal Molecular Clouds
  - Formation, evolution, & dissipation of GMCs? Does all MSF occur in clusters in GMCs?
  - Role of mag fields in MSF?
  - The IMF: What controls it in the MW? Is the IMF universal? Upper limit of the IMF? Dependence on initial conditions? (metallicity, density, available mass, turb, tidal forces, etc.)
  - Fragmentation vs turbulence in massive mol. cores? Is there an unbiased tracer?
  - Chemical changes vs observed line profiles during SF?
  - Are dust property changes during SF reflected in emission properties?

Synthesis of Problems in SF Continued

- Physics of Star Formation
  - Role of stellar mergers in MSF? How important? Do mergers & accretion occur together? Tests?
  - Accretion Disks: We need to know the velocity, temp., density, mass distributions vs time? Do massive protostars have disks? Do planets form around massive stars?
  - Bipolar outflows: physical properties vs time? How driven? Mass: recycled infall or entrained ISM? Origin: from disk, protostar, both, or neither?
  - Relationship of H_2O, CH_3OH, OH, SiO & NH_3 masers to MSF? What traces what?
  - Empirical formation & evolution sequence for massive stars? (equivalent to class 0, 1, 2, & 3 sequence for low-mass stars)
  - Triggered Star Formation: Time scales? Evidence?
  - Mass limits: Upper limit-dependence on metallicity, spin, environment? Minimum to become a WR*, black hole, & neutron stars?
  - SF efficiency: Dependence on feedback?
  - Stellar winds: When do they become important? Impact on environment?
  - Rotation: Impact on star formation & evoluiton?
  - Binaries & multiple systems: Formation? Mass transfer? Evol. of composition?
  - Runaway OB stars: How are they created?

The Three Most Important Problems in Star Formation? (A personal view)

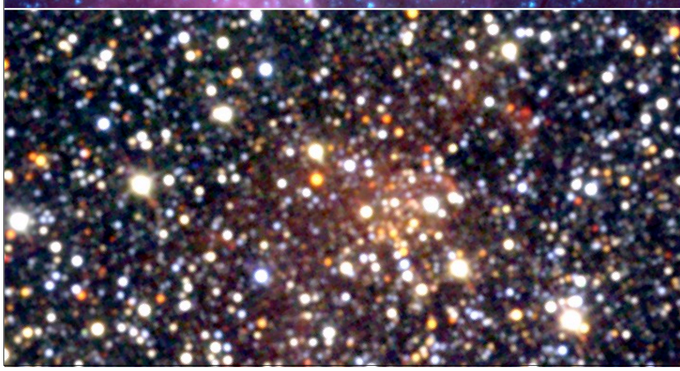
1. Formation of massive stars
   1. Role of mergers? Do mergers and formation by accretion occur simultaneously in the same cloud?
   2. How does matter actually get onto the central protostar?
   3. The disk-outflow connection? Role of B field?
   4. Formation of binary systems? Massive stars have binary fraction ~80% with M_1/M_2~1 in clusters
   5. Structure & Evol of accretion disks? High acc. rates=> disks recognition difficult even if present.
   6. Structure & evol. of bipolar outflows? How are they driven? Origin of their mass?
   7. An empirical formation and evolution sequence analogous to Class 0, 1, 2,&3 for low-mass stars
2. Understanding the IMF
   1. Is it universal?
   2. Star formation in a cluster environment?
   3. Dependence on initial conditions? (metallicity, turbulence, density, mass, etc)
   4. Upper mass limit?
   5. Formation, evolution, and dissipation of GMCs
   6. Fragmentation vs turbulent structure?
3. Star Formation at zero metallicity
   1. Properties of Pop III stars
   2. IMF dependence on metallicity
   3. Nature of natal clouds
4. The Starburst Phenomenon
   1. What drives them?
   2. What are their IMFs? Are the IMFs similar from galaxy to galaxy?
   3. Relationship to Galactic center clusters and SSCs?

Focus on the Physics of Star Formation: Main Problems
All require high spatial resolution & sensitivity

- Protostar formation
  - How does matter actually manage to reach the protostar?
  - Test formation theories (competitive accretion, protostar mergers, --?)
  - Prevalence of binary and multiple systems in OB clusters
  - Formation in a cluster environment?
- Disks
  - Formation & Structure with Time
    - Detailed velocity, temp., density, & mass distributions (protoplanetary gaps, accretion shocked surfaces, flaring, etc.)
    - Ionization structure
    - Evolution of the size, temp, & composition sist. of dust with distance from the protostar
    - Gas chemistry: molecular distribution with time and distance from the protostar to understand (chemical networks, possible chemical clocks, etc.)
    - Massive protostars: Do they have disks and if so, are they recognizable? Do they form planets? Formation via accretion=>controlled growth of protostar
- Bipolar Outflows (Jets)
  - How are they driven? (Structure at the base? Acceleration w/ distance?)
  - Velocity structure (entrainment), temp, density, mass distributions
  - Best atomic and molecular tracers (Which masers trace jets and which disks?)
  - Intermittent ejections--clumpy jets => accretion process
  - Extent (=> age, interaction with ambient ISM)--Remember HH34!

Relevant Observational Requirements

- Nearest low-mass star formation region ~100pc
  - Disk size: 50-500AU => need resolution~1AU => ~0.01"
  - To map disk structure (gaps, flaring, etc) need a few mas resol.
  - Spectral resolution ≤1 km/s
  - Want to detect masses ≤1 Earth mass
- Nearest massive star formation region ~ 450pc
  - Disk size:~500AU (?) =>need resol <5AU =>spatial resol <0.01"
  - Better resol. needed for more distant regions and to measure structure (thickness, gaps, flaring, etc)
  - Spectral resol. ~1 km/s
  - Need to detect masses ≤1 Earth mass/per resolution element)



Jets & Outlfows

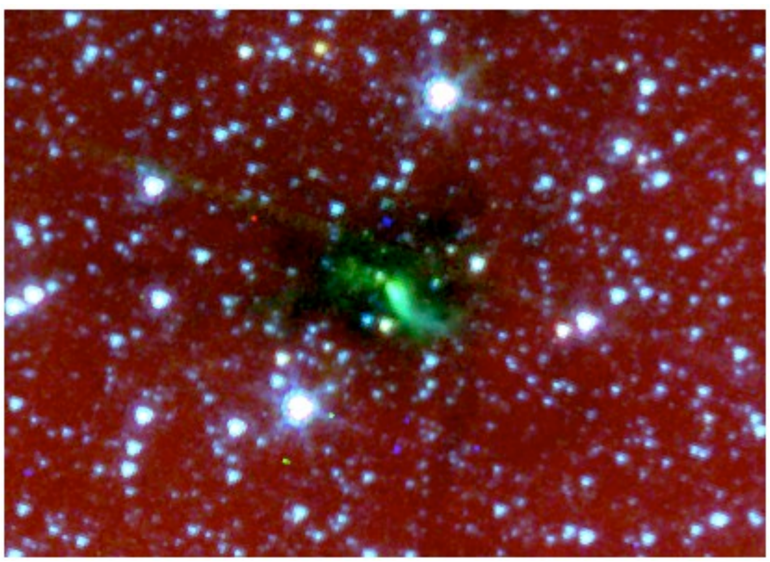
G320.23-0.29

GLIMPSE
Ch 1,2,4

Spitzer doesn’t have the exquisite resolution of HST, but it can observe objects at wavelengths that are are opaque to HST.

2MASS

Jet?



G34.26+0.15-Cometary UC HII

Ch 1,2,4

Multiplicity & Kinematics

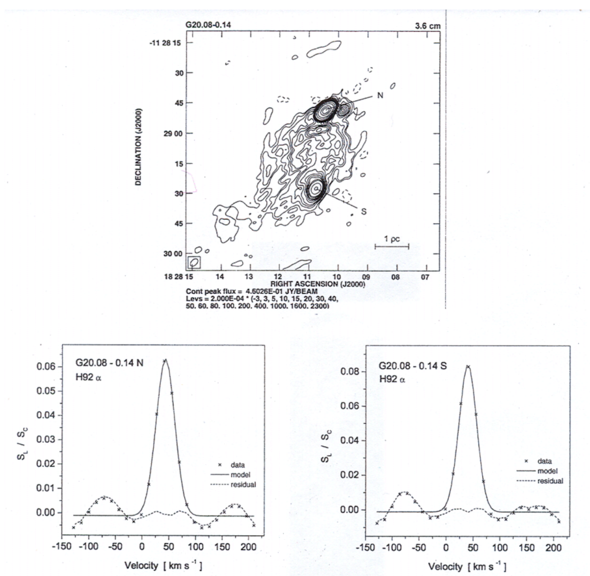


Fig. 3.5.— The 3.6 cm VLA continuum image and the integrated H92α line profiles from the N and S components of the continuum source G20.08−0.14.

Multiplicity & Kinematics

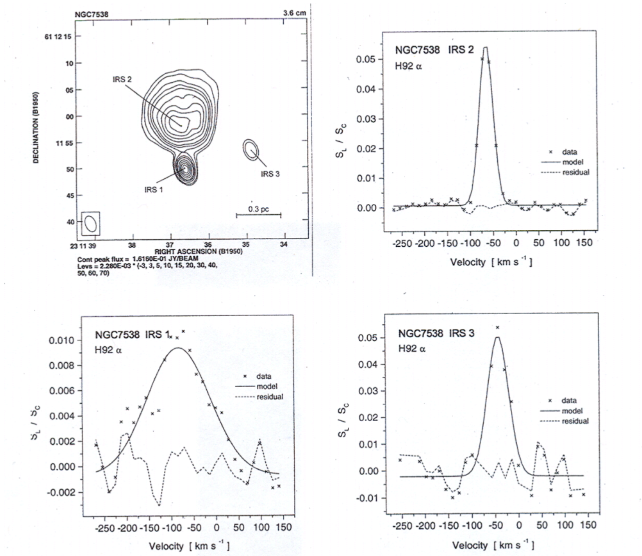


Fig. 3.8.— The 3.6 cm VLA continuum image and the integrated H92α line profiles from the IRS 1, IRS 2, and IRS 3 components of the continuum source NGC 7538.

Multiplicity

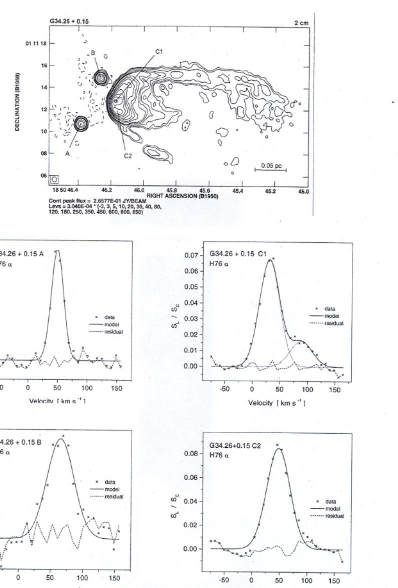
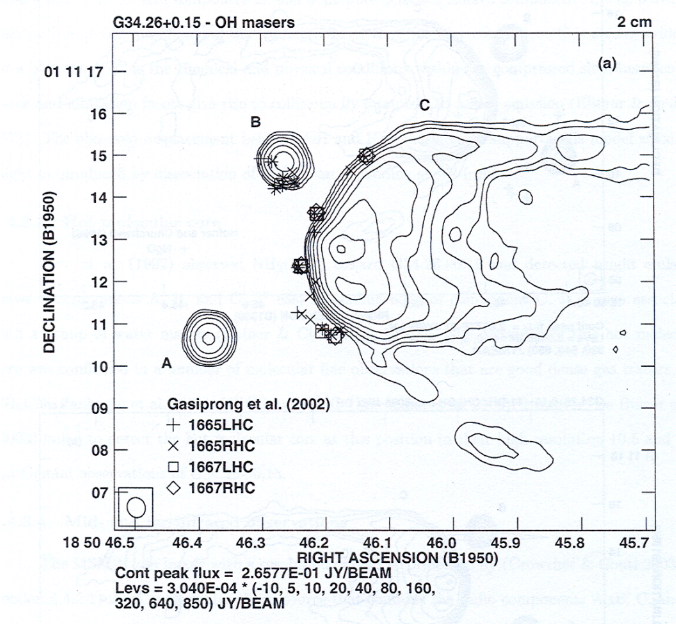


Fig. 3.9.— The 2 cm VLA continuum image and H76α lines toward four components in G34.26+0.15 massive star formation region. Note the large change in line width between A and the other components.

Masers & MSF

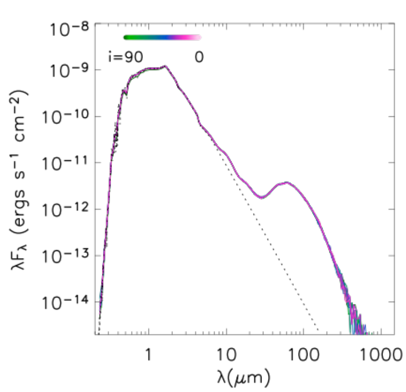


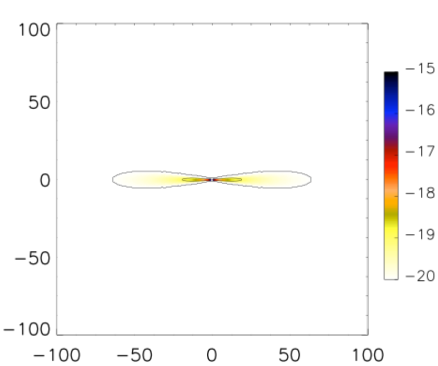
Class III <u>Model</u>

<u>Envelope</u>:
R=500 AU
M=2×10^{-5} Mo

<u>Disk</u>:
R=300 AU
M=2×10^{-8} Mo

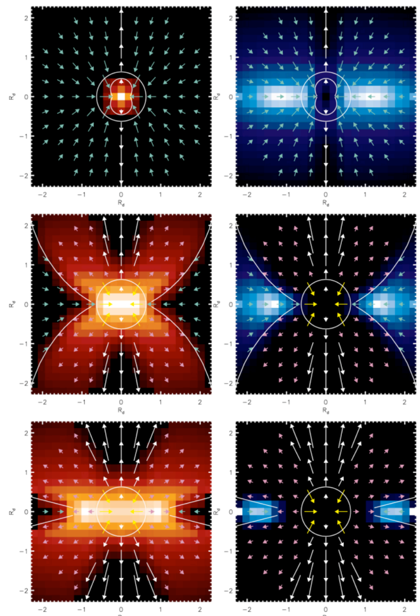
<u>Cavity</u>:
theta=90°
$n_{H2}=10^3$ cm^{-3}





Models of high angular momentum accretion flow
Keto (2006)

H^+ H_2



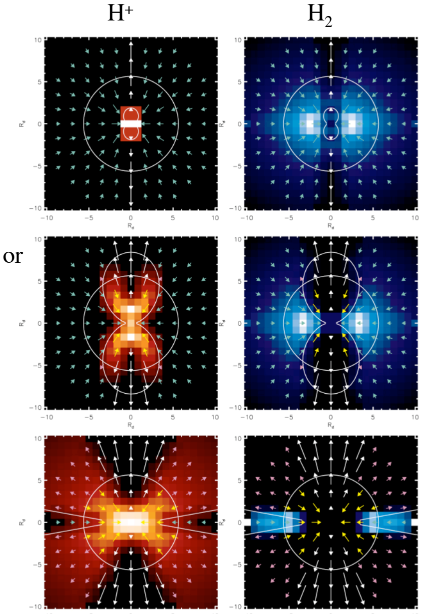
A gravitationally trapped HII region with a molecular disk. Low luminosity. Disk extends beyond the HII region.

A bipolar HII region with a molecular disk
Higher luminosity, disk extent decreases

A photo-evaporating disk
Still higher luminosity where disk is almost entirely within the HII region

Models of low angular momentum accretion flow
(Keto, 2006)

H^+ H_2

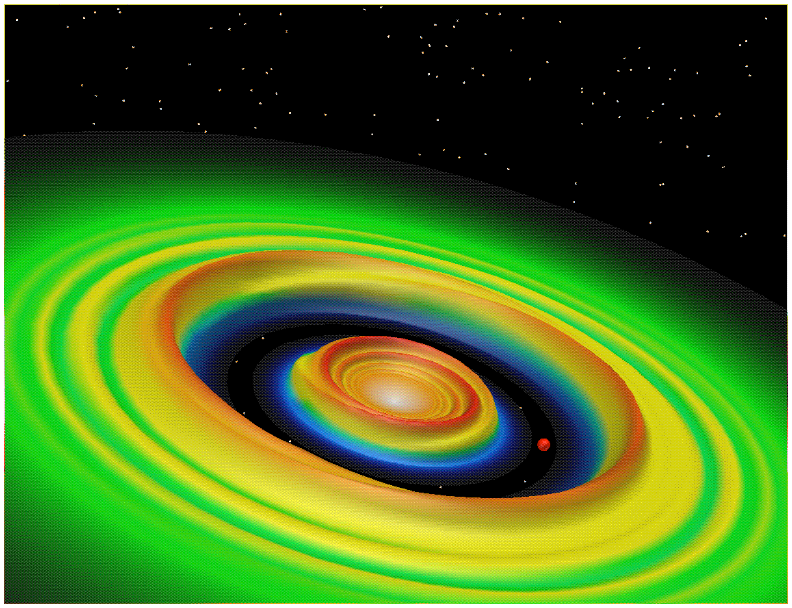


Gravitationally trapped HII region within a thick molecular disk or torus. Low luminosity case.

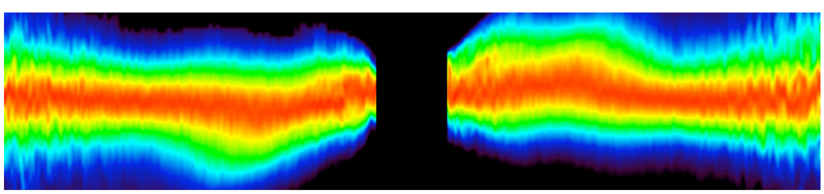
A bipolar HII region with a flared molecular disk or torus. Higher luminosity, thinner disk.

Still higher luminosity, thinner disk, disk formed Out of fully ionized gas, but near equator may be recombined.

Hydrodynamic <u>model</u> of a disk with a gap formed by a Jupiter sized planet (Bryden 2006)



An observed Debris Disk:
Beta Pic Disk

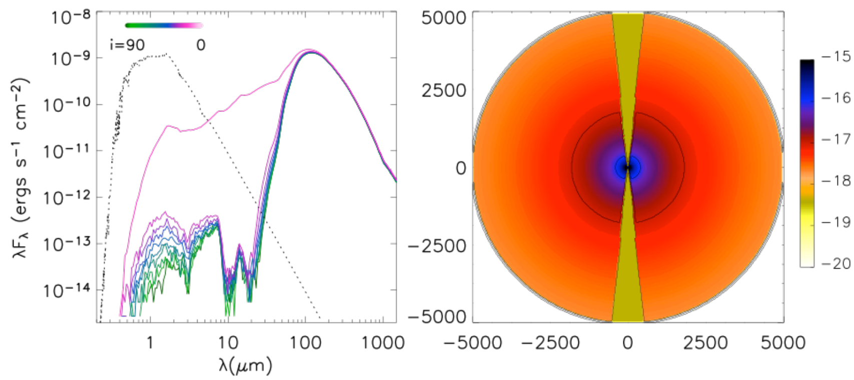


Class 0 Model

Envelope:
R=5000 AU
M=3.7 Mo
M=1x10^{-4}Mo/yr

Disk:
R=10 AU
M=0.01 Mo

Cavity:
theta=5°
$n_{H2}=10^5$ cm^{-3}

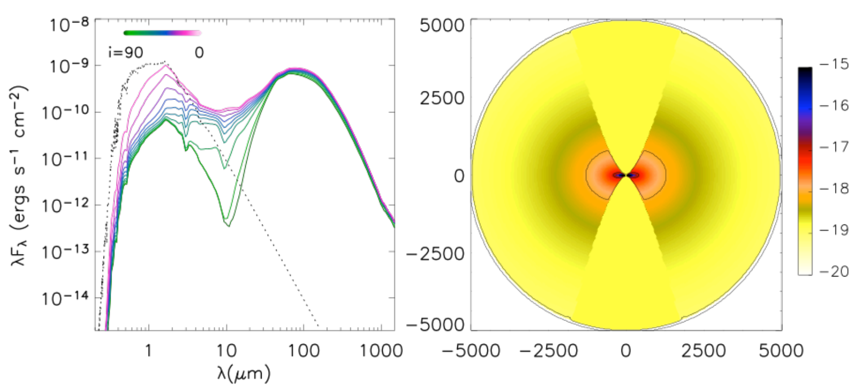


Class I Model

Envelope:
R=5000AU
M=0.2 Mo
M=5x10^{-6}Mo/yr

Disk:
R=300 AU
M=0.01 Mo

Cavity:
theta=20°
$n_{H2}=5\times10^4$ cm^{-3}

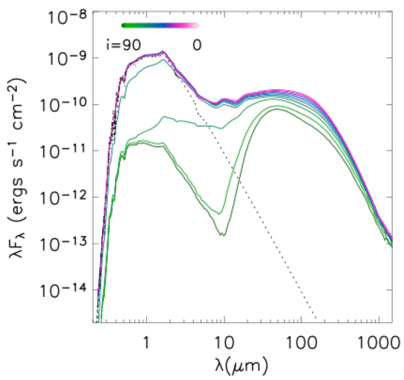


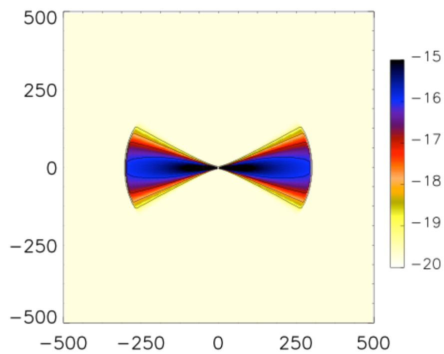
Class II Model

Envelope:
R=500 AU
M=10^{-4} Mo

Disk:
R=300 AU
M=0.01 Mo

Cavity:
theta=90^o
$n_{H2}=5x10^3$ cm^{-3}





Note

- The previous 4 slides (not including β Pic) are models!
- They are based on simplifying assumptions in the absence of high quality observational data
- A deeper understanding of star formation awaits detailed high resolution spatial and spectral line observations.

The Impact of Star Formation on the ISM and the need for high Spatial and Velocity Resolutions

- Distribution of matter & light: Constrains models of SF and ISM
- Dust distribution is filamentry: Drastically changes & complicates radiative transfer models (mean free paths of UV photons increased, mass estimates lowered, dynamical implications)
- Stellar wind, radiation, and bipolar outflows: Produce cavities around protostars and hot stars, form expanding bubbles that have complicated dynamics, morphological and ionization structures, produce shocks (bow shocks in massive star forming regions are common).
- Bubbles driven by hot star winds: Common in the disk of the Milky Way. Morphological properties imply information about the stellar wind luminosity, age of the central star(s), and density distribution of the ambient ISM. 24μm emission?
- The physical properties around protostars: Change over very small distances. The velocity structure is complicated with matter flowing both toward the star (acc. disk) and away from it (outflow). Density and temp change by orders of magnitude over radii from 0.1 pc to a few AU.

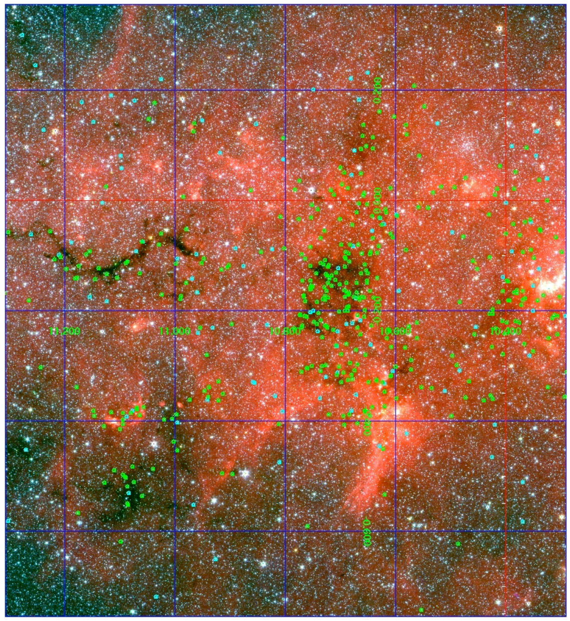
ISM

- Tracing IR Dark Clouds (cradles of star formation) via IR stellar colors
- Nebular Structure
  - RCW49
  - Orion
- Bowshocks
  - Orion
  - RCW 49
  - M17
- Bubbles
  - Spatial distribution:8µm vs 24µm
  - Morphology in IRAC bands
  - Triggered star formation?

Dark clouds at l~10.8 degrees
IR Dark Clouds defined by Stellar Distributions

Green->lower peak stars

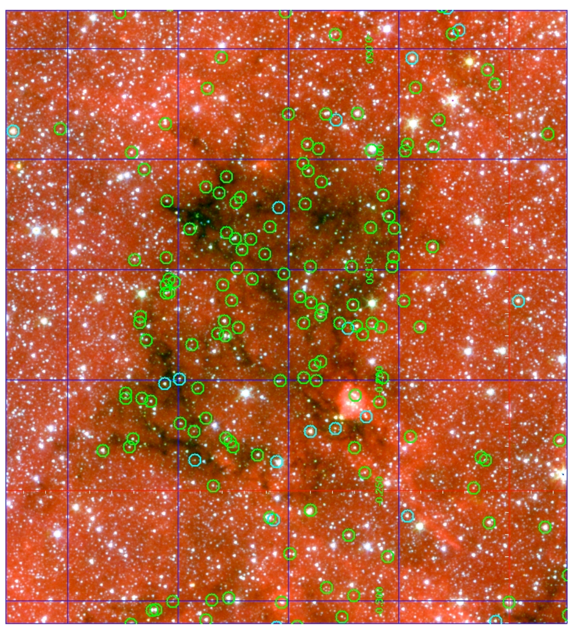
Blue-> upper peak stars



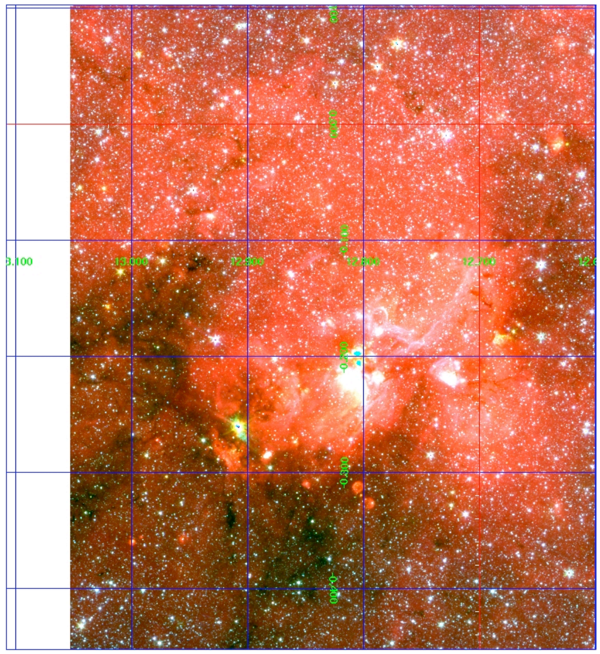
Stellar IR colors as tracers of Dark Clouds
A better tracer than silouettes

Green->lower peak stars

Blue->upper peak stars



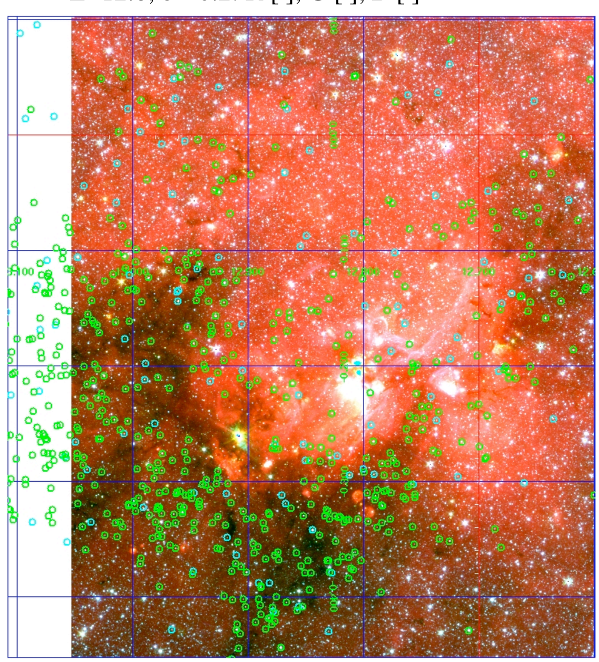
L=12.8, b=-0.2; R[ ], G[ ], B[ ]



L=12.8, b=-0.2: R [ ], G [ ], B [ ]

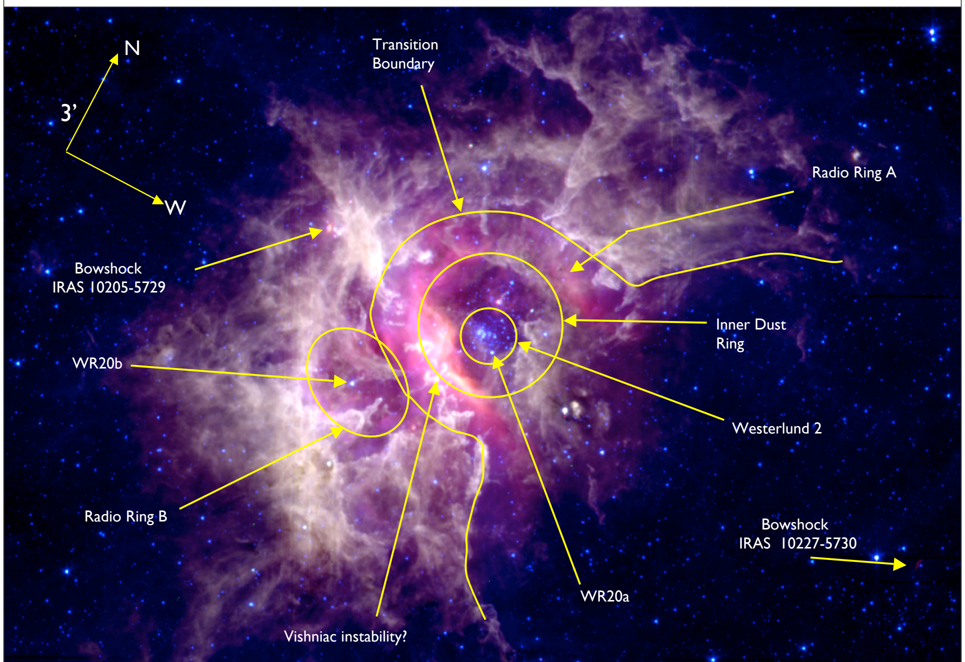
Green->lower peak

Blue->upper peak




RCW 49
123


RCW 49
234



Azimuthal Average Intensities

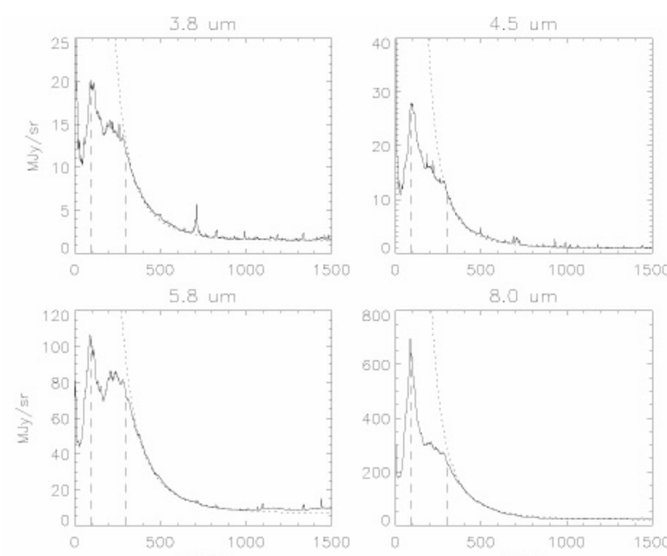
Θ>300" " ", <I> ~ θ^{-3}

=>consistent with $n_d \alpha\ r^{-2}$

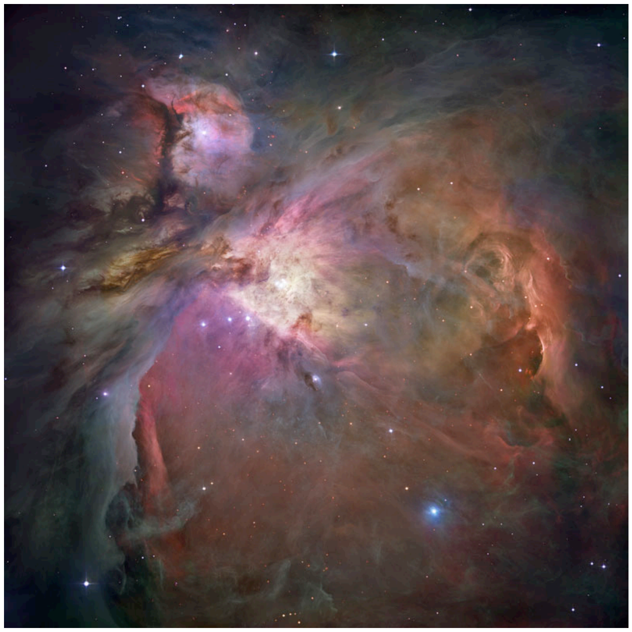
and dust emissivity

$\varepsilon_d\ \alpha\ n_d/r^2\ \alpha\ r^{-4}$

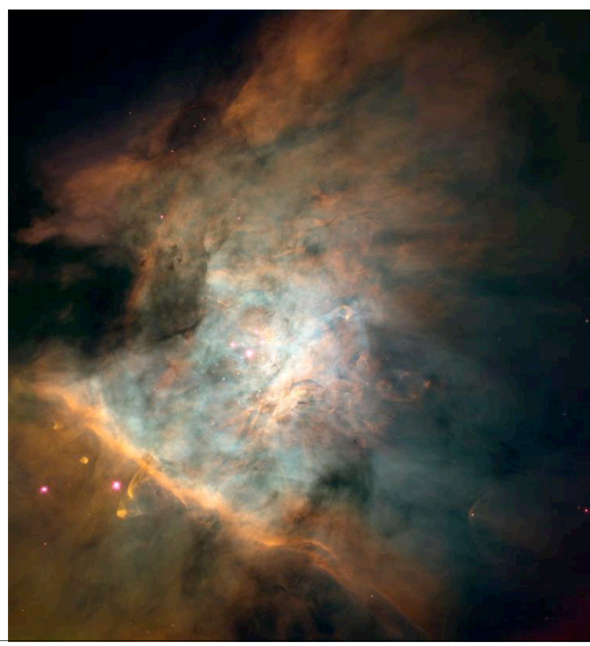
(Dilution of the radiation field $\alpha\ r^{-2}$)



Large Scale Nebular Structure: Orion

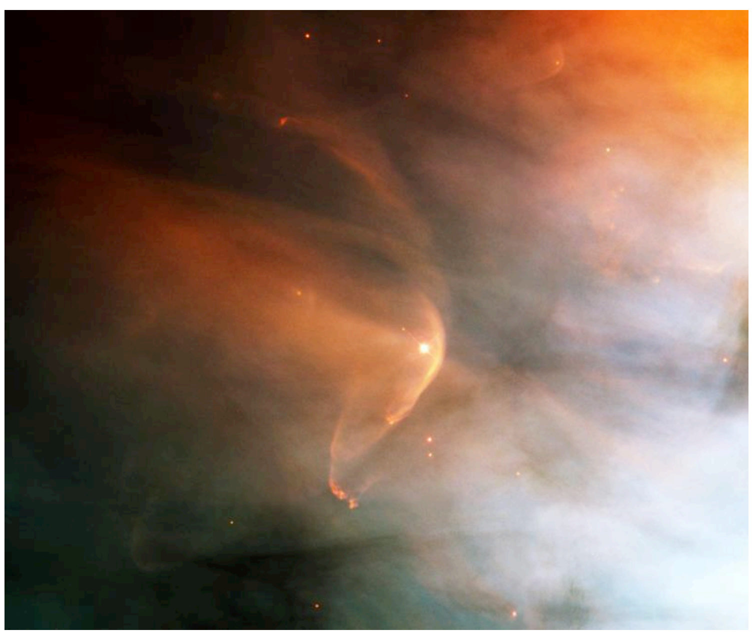


The Bar and the Bay in Orion



Fine Scale Structure in Nebulae: Orion (HST)

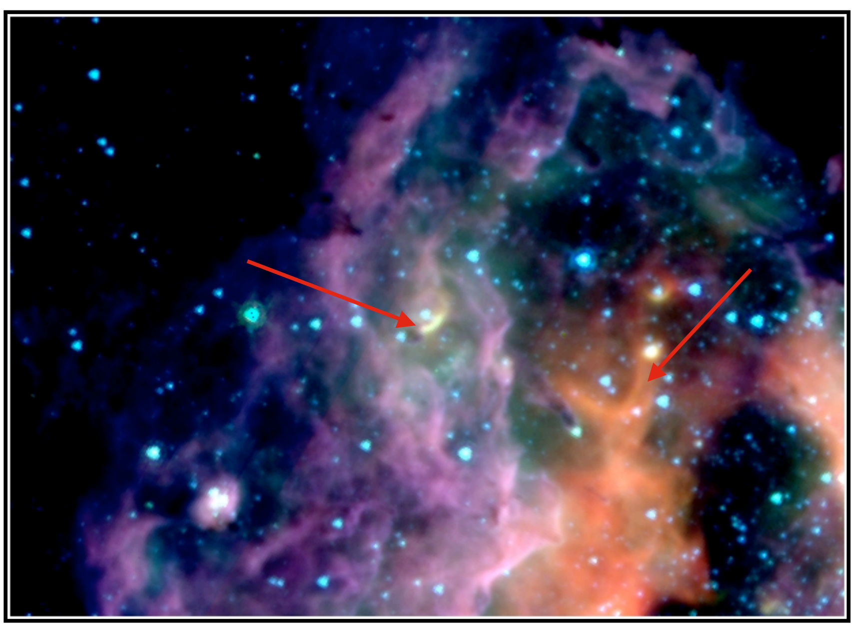
Bowshocks are common in Nebulae: Orion



RCW49

Bowshocks are common in Massive Star Formation Regions

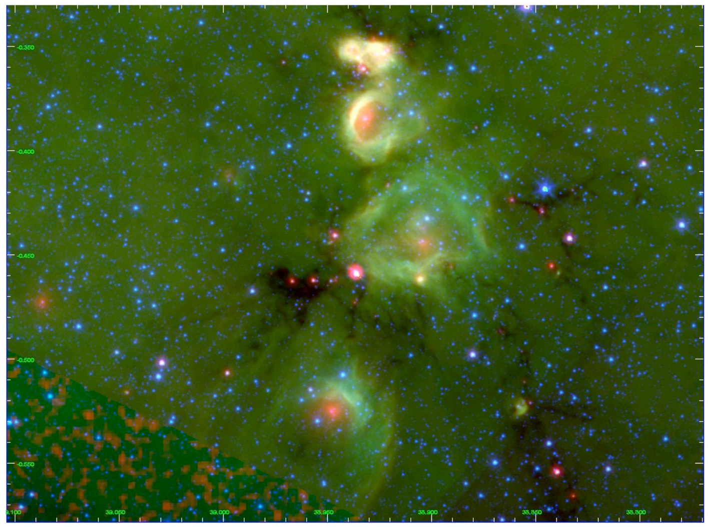
Bowshocks in M17 (IRAC1, 2, & 4)



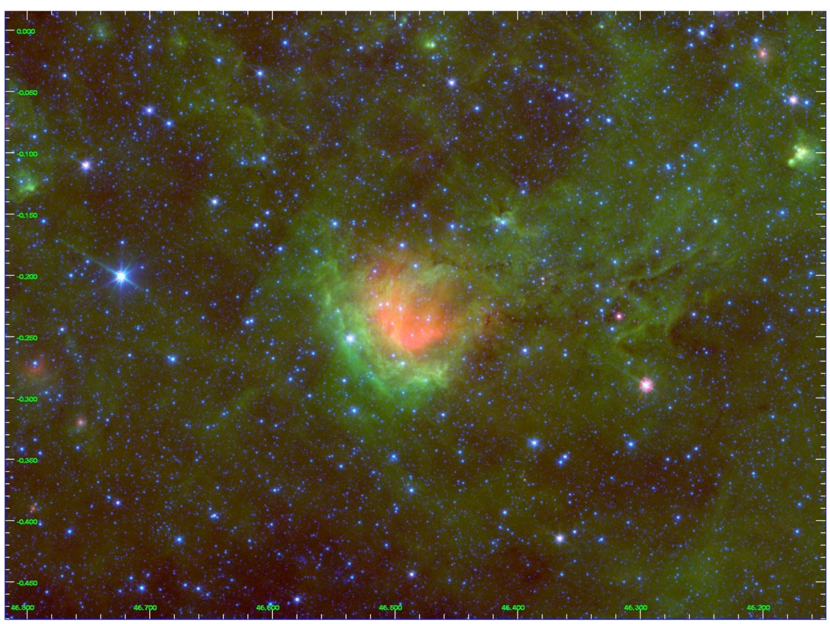
MIR dust bubbles (4.5, 8.0, 24μm): G38.9-0.45

8μm more extended than 24μm

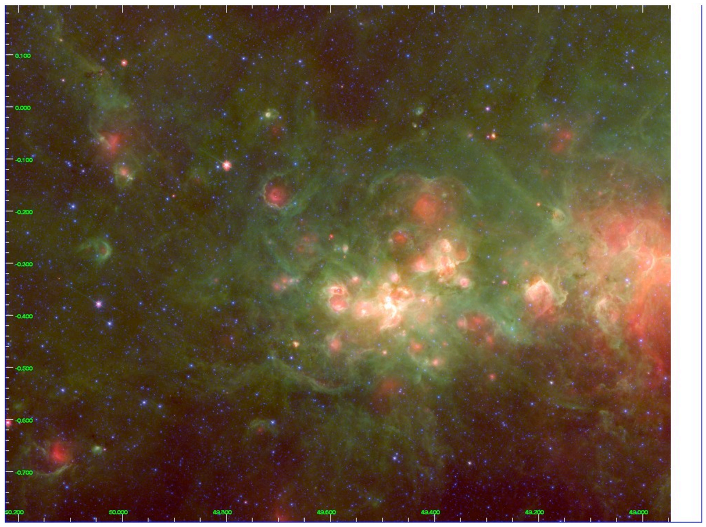
24μm confined to the central part of bubbles



MIR dust bubbles:G46.5-0.25



MIR dust bubble:G49.5-0.4



MIR dust bubble:G51.0-0.0

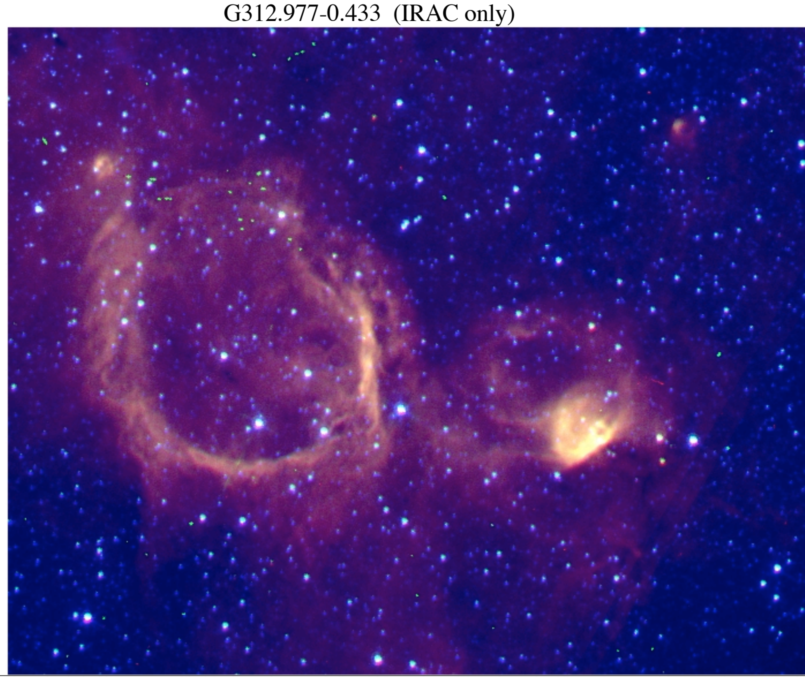
MIR dust bubble:G52.2+0.7

So what's going on with dust emission in these bubbles?

- Given that 8μm emission is very extended and 24μm emission appears to be confined to regions surrounding hot stars or clusters,
- Consistent with
  - 24μm emission from thermal dust emission plus ~10% from transiently heated small grains supplied by OB star(s)
  - 8μm emission dominated by PAH emission: distribution => a PDR tracer, destroyed near hot OB stars
- How does the dust giving rise to 24μm emission survive in the vicinity of OB stars? Why aren't they evacuated by the winds and radiation from OB stars?

But what about the G14.1-1.13 region?

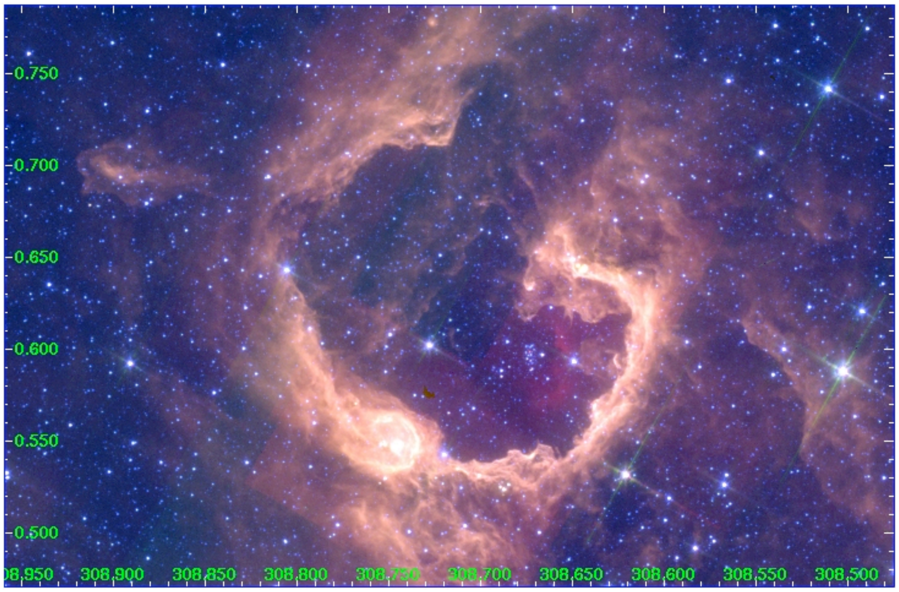
The Galactic plane is rife with dust bubbles such as
G312.977-0.433 (IRAC only)

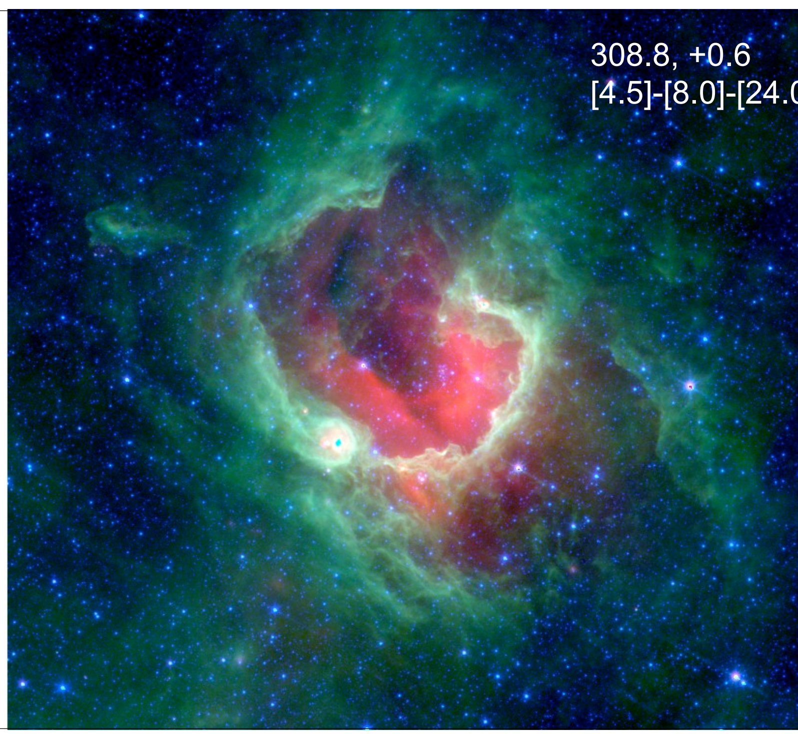


And G309.049+0.162-center; Diam~0.2 deg

G311.485+0.397:Triggered Star Formation?

RCW79: An example of Triggered Star Formation?





Origin & Nature of the Bubbles

- Overwhelming majority are produced by the winds and radiation pressure from O and B stars.
  - Out of 322 bubbles cataloged from the GLIMPSE survey
    - 25% coincide with radio HII regions (=>B3 and hotter stars)
    - 13% enclose known open clusters (OB associations)
    - Most of the rest appear to be produced by B4-B9 stars
    - Only 3 coincide with known SNRs
    - None coincide with Planetary Nebulae or WR stars
- Given that at least 25% of the bubbles coincide with an HII region and ~13% with an OB cluster, the24μm emission distribution raises some puzzeling questions
  - How can the grains survive in the intense UV radiation fields of OB stars?
  - Why aren't these grains swept out to the outer shell by OB winds?

Theory: bubble structure and evolution

- Large scale structure,
- Weaver et al. (1977)

Wind shocked region:
Chandra Con-X
XMM
Shell:
ALMA SPITZER
SOFIA Herschel
JWST

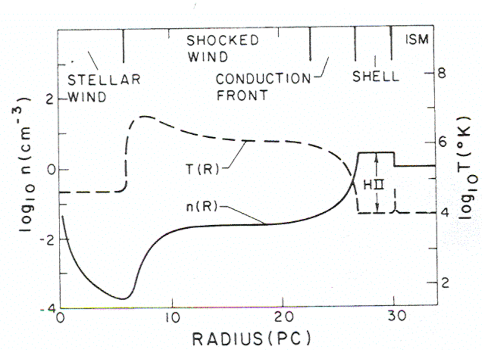
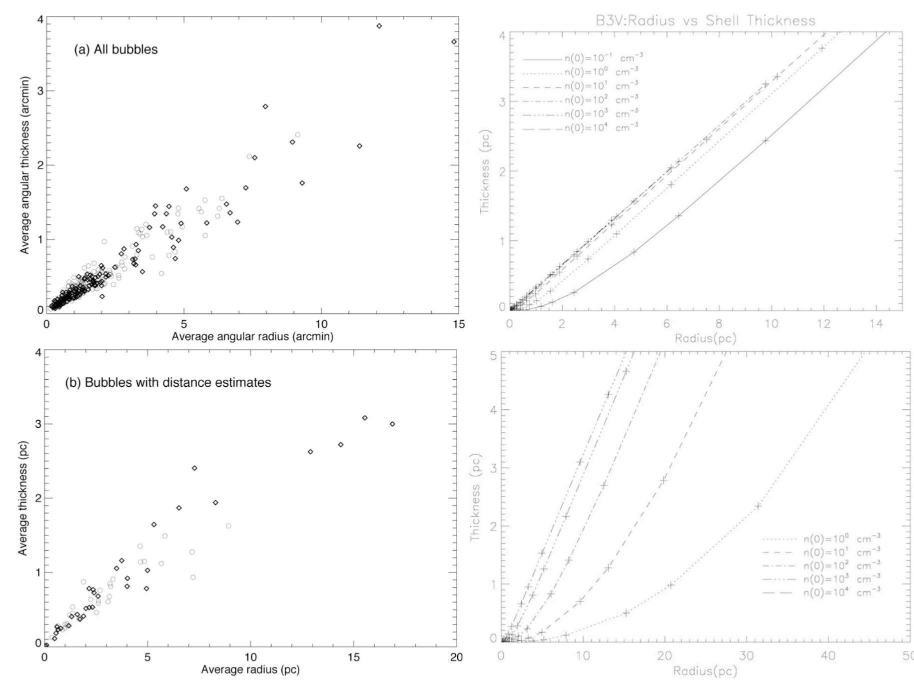
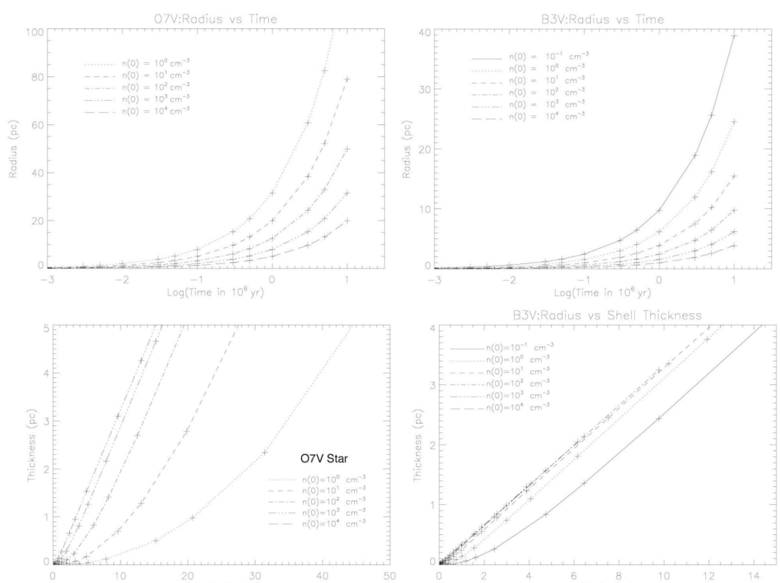


FIG. 3.—The large-scale features of the temperature and density structure of an interstellar bubble for which $L_w = 1.27 \times 10^{36}$ ergs s^{-1}, $n_0 = 1$ cm^{-3}, and $t = 10^6$ yr. ISM means ambient interstellar medium. For a typical O7 I star, the H II region would extend to $\sim 3\ R_2$.



Bubble Evolution: Size & Thickness vs Time

Weaver et al. (1977) for uniform density ISM



The Great Observatories

- SOFIA
  - FLITECAM:1-5.5μm, FOV=8'
  - GREAT: high res. Spectroscopy
    - 127-157μm; 124-111μm; CII-158μm OI 63μm
  - FORECAST:FOV=3.2'x3.2', resol=2.5"
    - mid-IR Cam. 5-8μm; 17-25μm; 25-40μm
  - Others: SAFIRE; EXES; CASIMIR; HAWC; FIFI
- ALMA
  - 30-950GHz; 150m-14km; resol;mas-14"
  - 64x12m antennae
- CON-X
  - 4-tel array; 0.25-40 kev; high resol&sens.
- JWST
  - 6.5m tel; 0.6-28μm; L2; resol=0.1"
  - NIRCAM, NIRSpec, MIRI, FGS
- VISTA
  - 4m tel, FOV=1.65^0, 0.34"x0.34"
  - Z, Y, J, H, Ks (NIR)
- LSST
  - Opt. Survey tel, FOV=3.5^0,
  - U,G,R,I,Z,Y; whole sky every 3 nights
- Herschel
  - 3.5m tel, L2, 3yr mission
  - PACS, SPIRE, HIFI
- GSMT
  - 30-50m tel, diffract lim >1μm
  - Very sensitive & high resol.
  - Not many details

Summary for Great Observatories

- ALMA & CARMA-essential high resolution imaging of continuum, atomic & molecular lines at mm & submm wavelengths where MSFRs are optically thin.
- SOFIA-essentially every instrument forseen for this facility will be important for star formation, bubbles, & ISM studies. Wavelength coverage from NIR to Submm, imaging and high res. spectroscopy.
- Con-X and Chandra-essential to image the hot wind shocked gas in HII regions and bubbles and to understand the large population of hard X-ray sources in MSFRs, hot-cold gas interfaces, shocks, etc.
- JWST-visual to mid-IR (0.6-28µm) imaging and spectroscopy with high spatial and spectral resolution (R=100-3000) with high sensitivity(6.5m aperture; more sensitive than SOFIA & Herschel). ALMA, SOFIA, Herschel, & JWST will be complimentary
- Herschel-FIR imaging photometry and high spectral resolution spectroscopy at submm wavelengths. Will be a major player in the study of SF and nebular structure if it works as projected.
- SPITZER-is providing a broad basis for the facilities at left. It doesn't have the spatial resolution to resolve disks but is providing info on global questions such as the Gal. dist. of SF, the rate of SF in the Galaxy, the spatial relationship between dust & SF,YSOs via outflows, impact of MSF on the ambient ISM, etc.
- VISTA-a fast wide FOV survey telescope at NIR wavelengths. Probably less useful for SF studies than those in the left column, but might be useful to monitor variability and angular expansion rates of bubbles around YSOs if not too obscured.
- LSST- a large UV-NIR survey telescope. Probably not especially useful for SF and embedded nebular studies. Should be useful for measuring angular expansion rates of visible HII regions and bubbles.