
FALLOUT FROM
THE PHIL ZONE

"Modern" Paradigm of Star Formation is 250 Years Old

- Kant-Laplace Nebular Hypothesis
  - Clouds of interstellar gas and dust collapse to form stars via gravitational instability
  - Rotating clouds collapse into disks
- Gases and solid matter in disk form planets
  - Rocky planets in warm, inner solar system
  - Gas giants in cold, outer solar system
- Strong basis to expect stars with retinue of planets

Until 1970-80s there was LITTLE observational evidence for this hypothesis

State of Play in 1960s

- Young OB stars and HII regions from optical spectroscopy and radio continuum, e.g. visible and obscured HII regions, such as Orion, W3-W5
- Bright and Dark nebulae identified on POSS
  - Bok Globules (Bok, 1947,ApJ, 105, 255)
  - Sharpless HII regions (1959, ApJ(S), 4, p.257)
  - Lynds (1965 ApJS, 12,163) & Barnard (1927)
- Young, low mass stars identified through nebulosity and proximity to OB associations
  - Herbig Ae/Be stars, T Tauri stars, HH objects
- ISM probed only through diffuse 21 cm HI gas

Peculiar Variable Stars: “Objects of Joy” (1945)

11 variable stars showing common characteristics:

1. Light variations of ~3 mag
2. Spectral Type F5-G5 with “chromospheric” emission lines
3. Low luminosity
4. Association with dark or bright luminosity
5. Situated in or near Milky Way dark clouds

T TAURI VARIABLES

STAR	α (1900)	δ (1900)	MAGNITUDE RANGE	GALACTIC l	GALACTIC b	REMARKS
RW Aur	5^h $1^m.4$	+30° 16′	9.0–12.0	142°	− 6°	Double
UY Aur	4 45.4	+30 37	*11.6–14.0*	139	− 8	Double
R CrA	18 55.1	−37 6	9.7–13.5	328	−19	Nucleus of variable comet-like nebula, NGC 6729
S CrA	18 54.4	−37 5	9.5–13	328	−19	Double
RU Lup	15 50.1	−37 32	*9.0–11.0*	307	+11	
R Mon	6 33.7	+ 8 50	9.3–14.0	171	+ 3	Nucleus of variable comet-like nebula, NGC 2261
T Tau	4 16.2	+19 18	9.0–12.8	148	−22	Near Hind’s variable nebula, NGC 1555, and surrounded by a small shell
RY Tau	4 15.6	+28 12	8.8–11.1	136	−14	Nucleus of a fan nebula
UX Tau	4 24.2	+18 0	*10.5–13.4*	146	−19	Double
UZ Tau	4 26.6	+25 40	9.2–<13	140	−14	Double
XZ Tau	4 25.9	+18 1	*10.4–13.5*	146	−19	

A. H. Joy 1945, ApJ, 102, 1068

The Revolutionary Era:
The Late 60s --- Early 70s

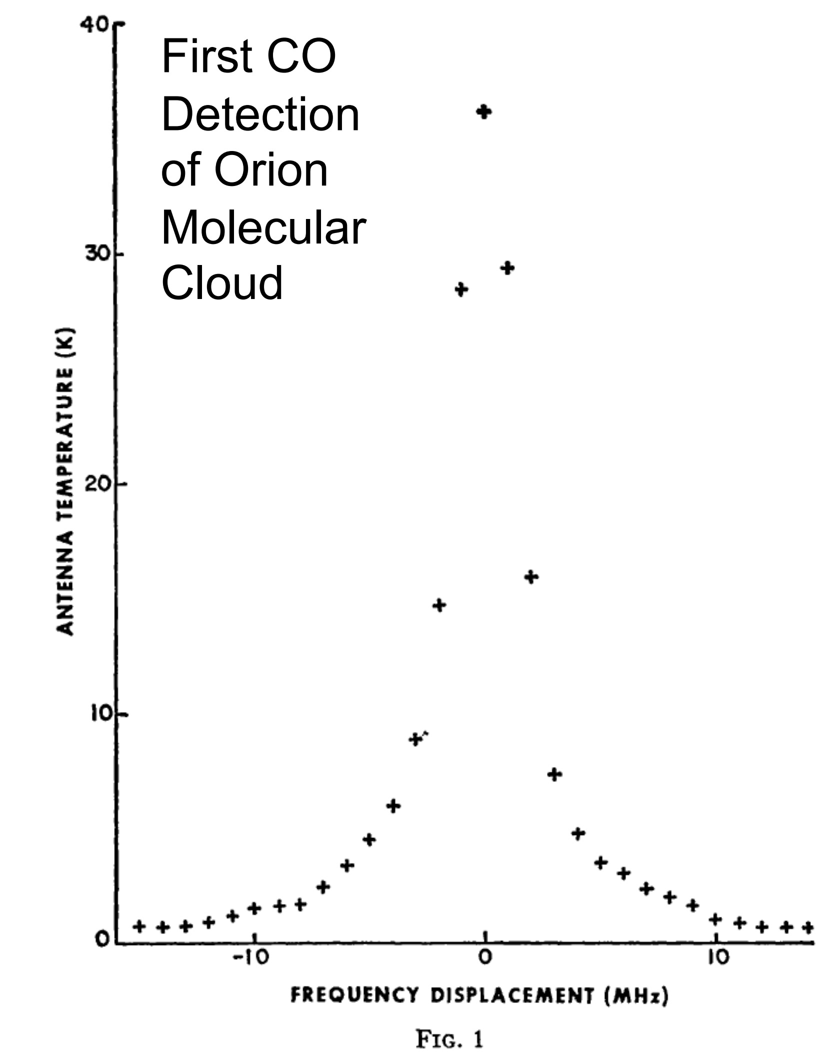
- Millimeter spectroscopy
  - Giant Molecular Clouds
  - Dense Cores
  - Composition & Physical Conditions of gas
- Infrared astronomy
  - Probe Dark clouds
  - Embedded sources
  - Composition & Physical Conditions of dust

DRUGS, SEX, ROCK & ROLL

The Late 1960s: Molecular Line Astronomy

Review by Rank, Townes, Welch, 1971, Science 174,1083

- CH (1937) & CN (1941) in visible
  - CN from excited state 2.7K above ground state (who knew!)
- Radio lines started with HI (21 cm; Ewen and Purcell 1951) and OH (18 cm; Weinreb et al 1963)
- With NH_3 (1.3 cm; Cheung et al 1968) and CO (2.6 mm) probing gas with n >10^3 cm^{-3} , T~ 10-100 K, ***the idea of the molecular cloud was born***



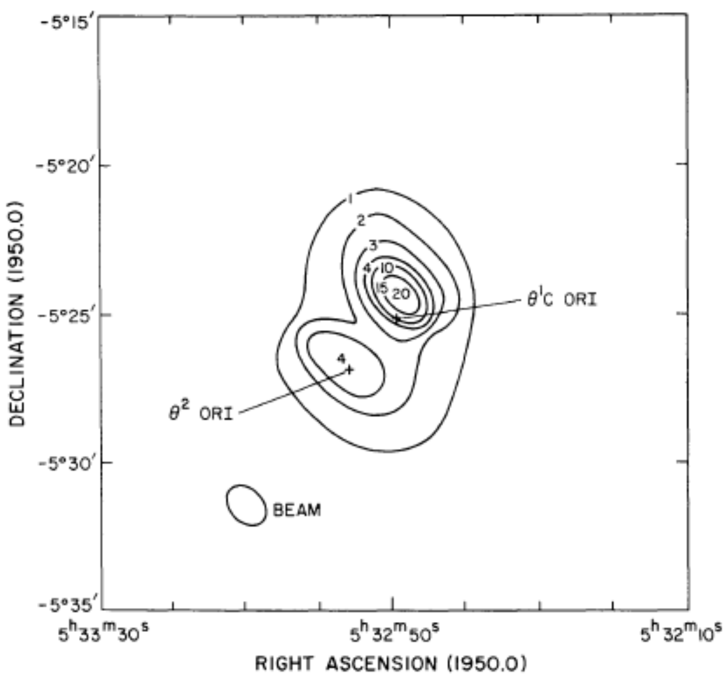
Wilson, Penzias, Jefferts, 1970

Late 1960s: Infrared Astronomy

Single pixel bolometer "arrays" and strip charts revealed embedded "protostars" within molecular clouds

A HIGH-RESOLUTION MAP OF THE ORION NEBULA REGION AT FAR-INFRARED WAVELENGTHS

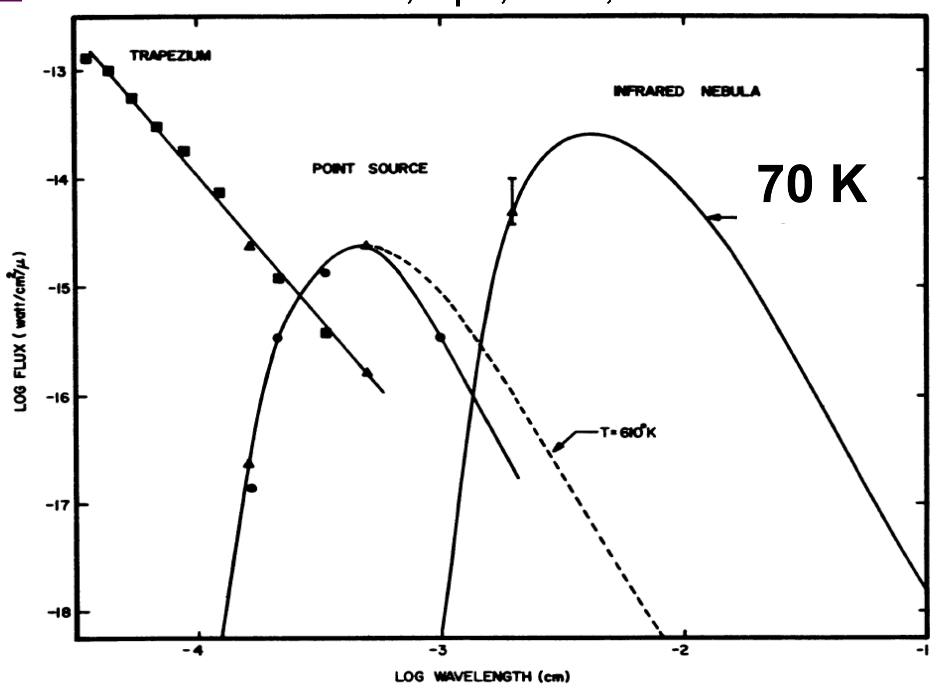
Fazio et al 1974, ApJ, 192,L23



DISCOVERY OF AN INFRARED NEBULA IN ORION

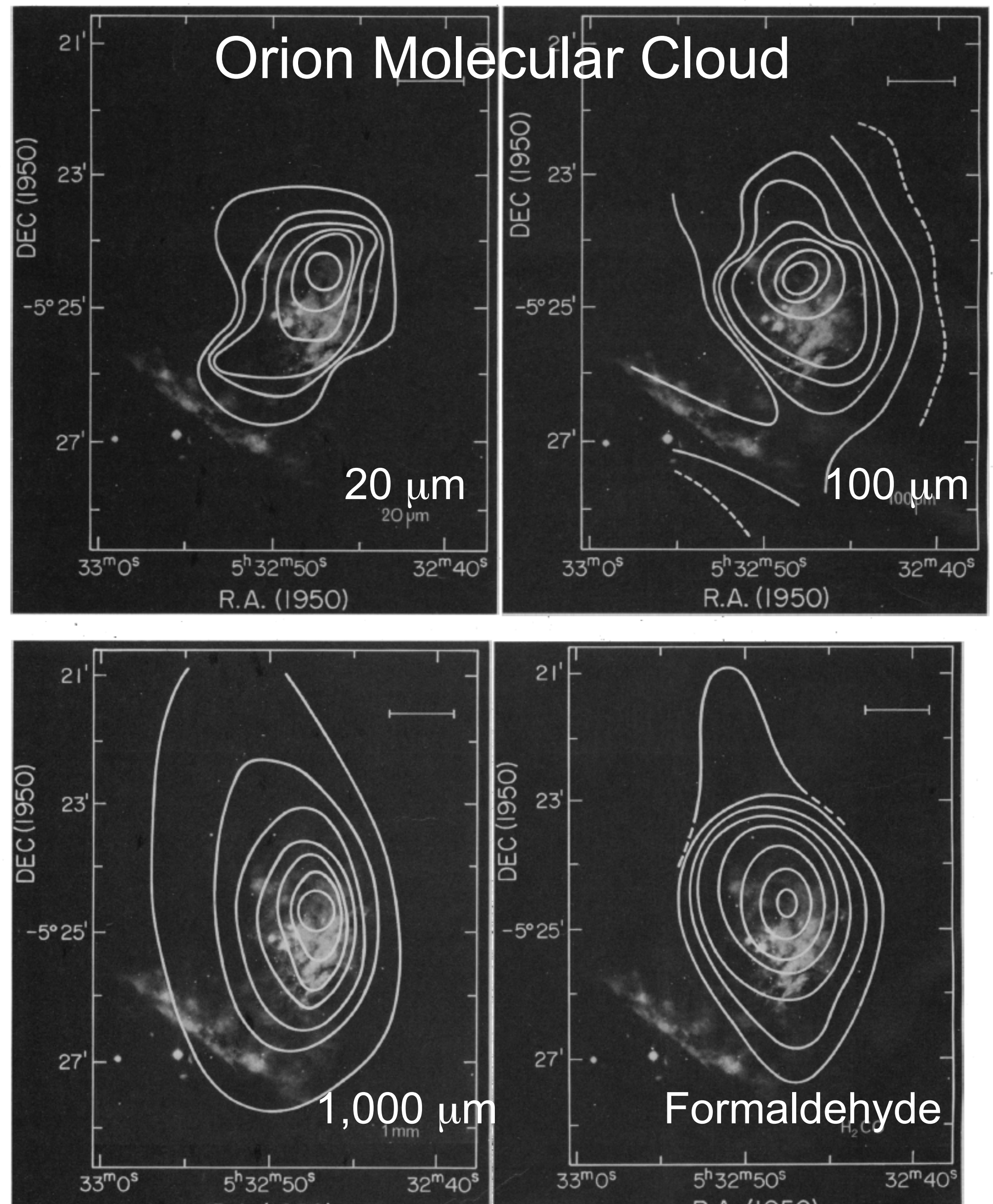
D. E. KLEINMANN
Department of Space Science, Rice University
AND
F. J. LOW

1967, ApJ, 149, L1



Giant Molecular Clouds

- GMC's (10^4-10^5 M_o) with luminous IR sources (10^4-10^6 L_o), 1-10 pc across with ~10^4 M_o of gas --- birthplaces of OB stars and clusters
- A few compact objects (W5-IRS1, BN) with lower L ~$2x10^3$ L_o, little ionized gas
  - Likely fully formed, but embedded stars

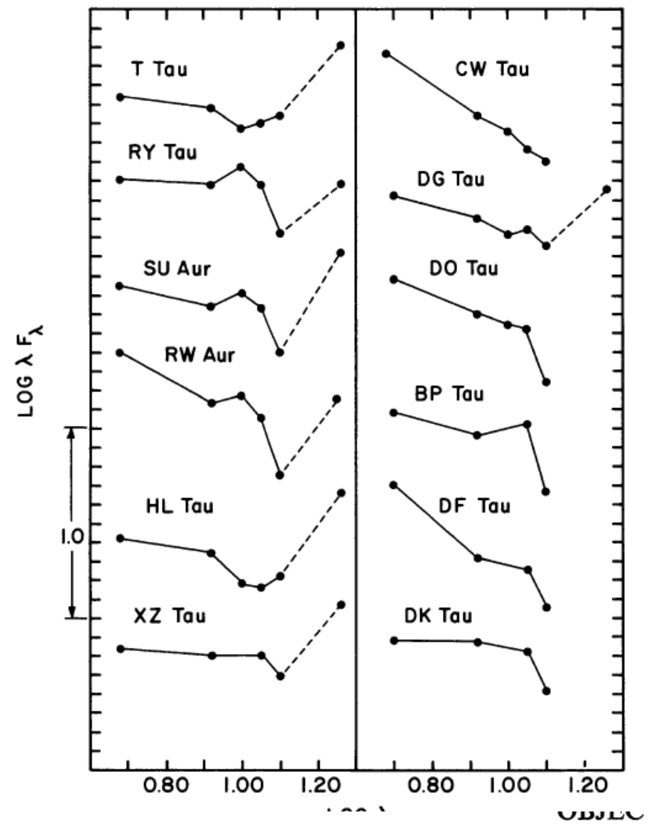


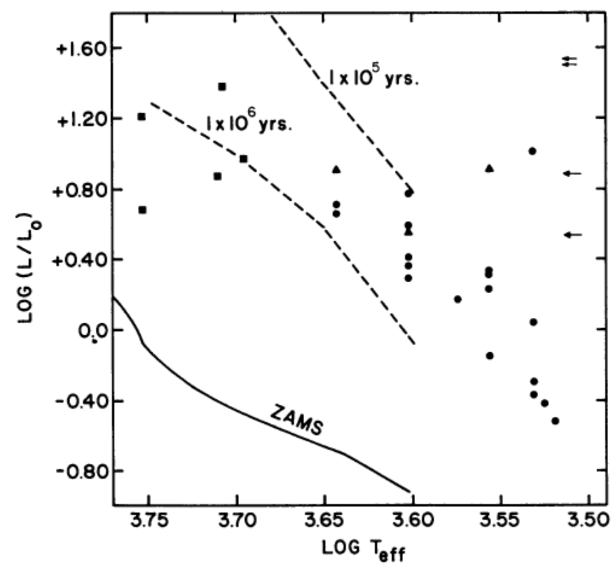
Werner, Becklin, Neugebauer 1977, Science, 1977,723

"Objects of Joy" (T Tauri Stars) As Young Stars

- When corrected for Av, T Tauri stars have (L, Teff) consistent with 1-3 M_o stars evolving toward main sequence
- Hot gas from accretion
- IR excess from dust including silicates and ices

Rydgren, Strom, Strom
1976 ApJS, 30,307





George Herbig

Herbig Haro Objects

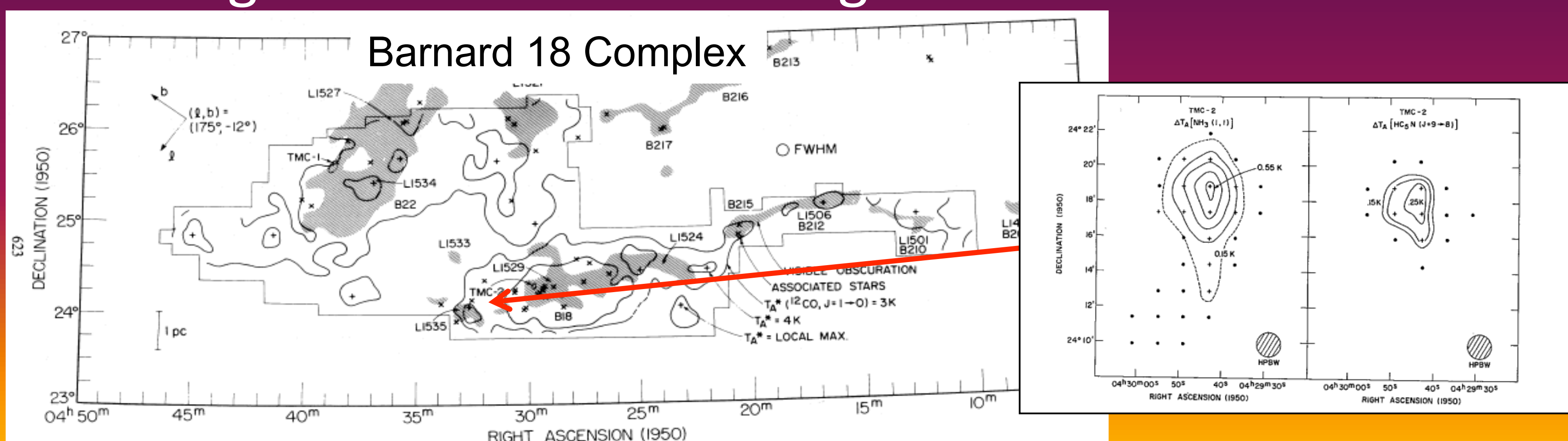
Guillermo Haro

- Bright, non-stellar knots of emission associated with young stars and dark clouds
- Continuous or low excitation emission lines
- No obvious stellar source

- HH Objects indicative of obscured, low luminosity young stars, e.g. Strom, Grasdalen, Strom 1974 (ApJ, 191, 111)
  - IR-only sources displaced away from HH object
  - Emission line RV suggest mass loss
  - Parent s of nebulous objects & grandparents of T Tauri stars?
  - → **Dark clouds evolve from dense condensations (CS gas) to lower density clouds with T Tauri stars at later stage of evolution**

Enter Our Heroes: Dense Cores in Taurus

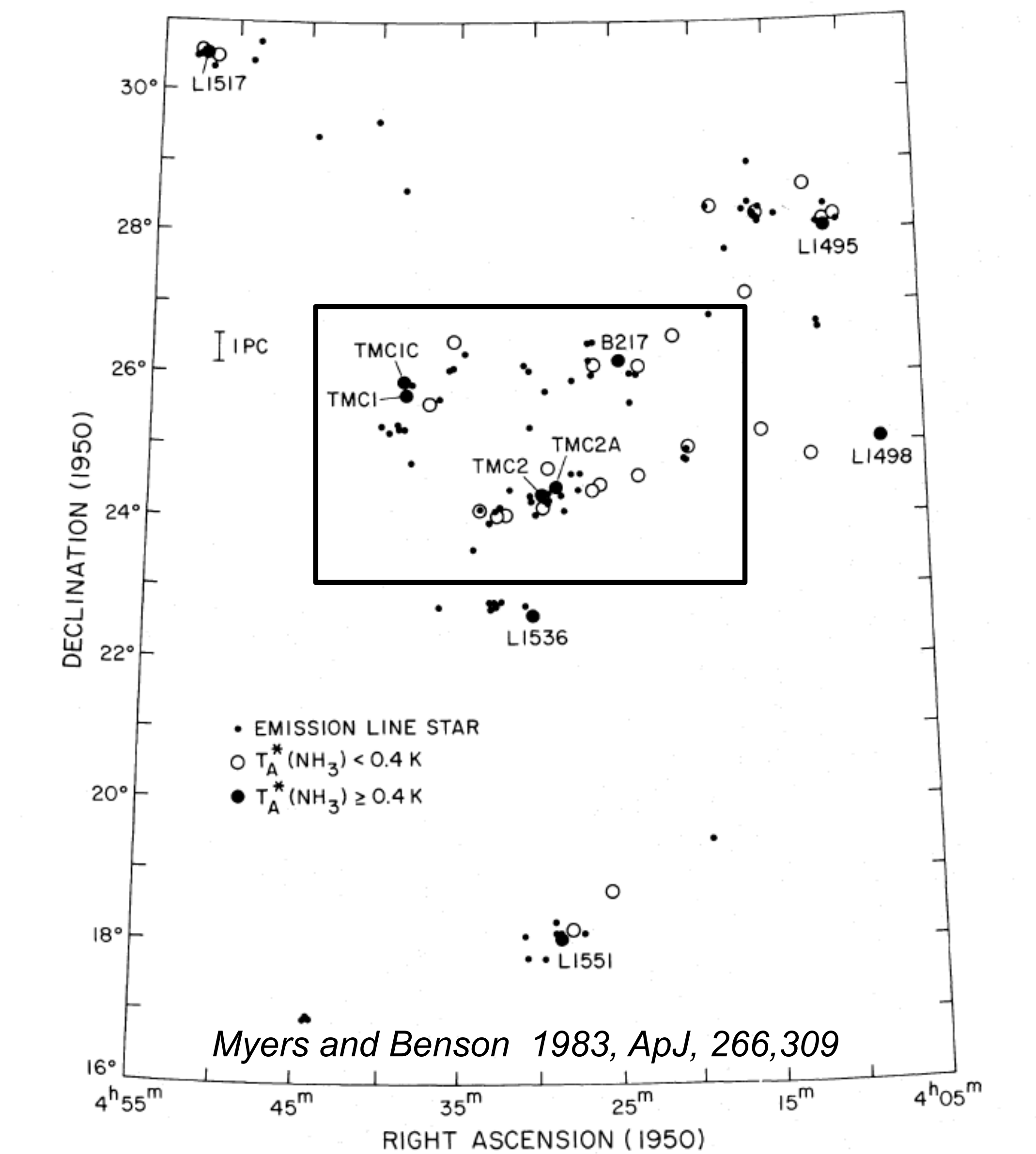
- Molecules throughout B18 complex of dark/light clouds
  - Low density areas: 2 x5 pc , <700 cm^{-3} , Av~2-3 mag, 600-700 M$_o$
  - High density regions: ~0.7 pc, 3 ×10^3 cm^{-3} , Av~10 mag, 100-200 M$_o$
  - Extreme high density (HCO^+, NH_3): 0.1 pc, ~4x10^4 cm^{-3} , 1 M$_o$
- T Tauri stars suggest star formation efficiency of 1% near diffuse gas and 2% near dense gas. But selection effects!



Myers et al 1982, ApJ, 257,620; Myers, Ho and Benson, 1979, ApJ,233, L141

The Dense Core Catalog

- A series of over 20 papers (1978-1983) culminated in a survey of >100 dense cores:
  - Diameter =0.1 pc,
  - Mass ~$4M_o$
  - Density ~3×10^3 cm^{-3}
  - T~11K
  - Δv~0.3 km/s
  - Free fall time ~2×10^5 yr.
  - Assoc w. Em line stars
- These became the basis of IRAS dense core program

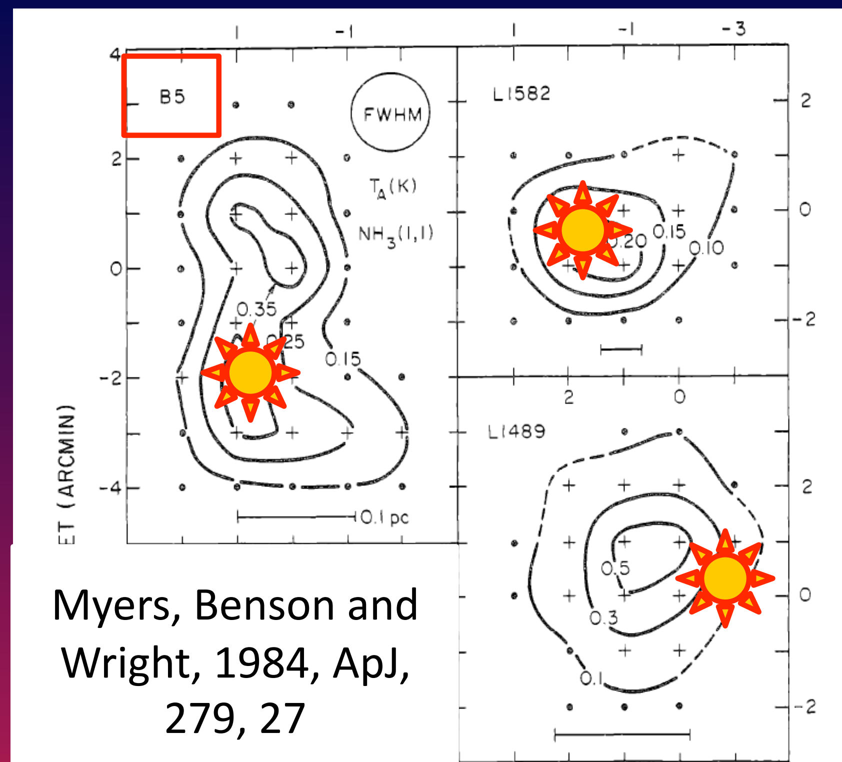


Myers and Benson 1983, ApJ, 266,309

"A Survey For Dense Cores In Dark Clouds"
Benson & Myers, 1989 ApJ(S), 71, 89
-Phil's #1 paper with 441 Citations

Initial IR Search of Dense Cores

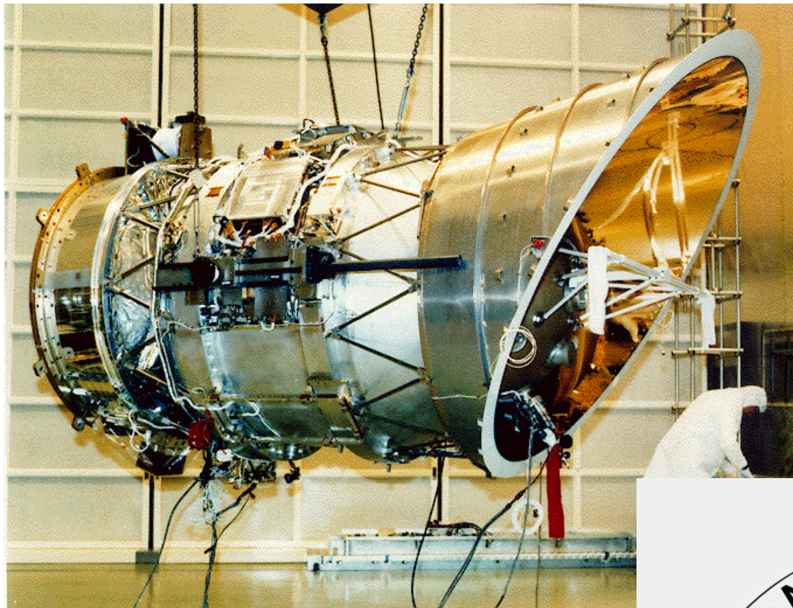
- Phil, Priscilla, and Ned Wright (1984) scanned 25 dense cores at 2.2 μm
- Found 3 optically obscured sources with luminosities 2-3 L_o at or near center of cloud core

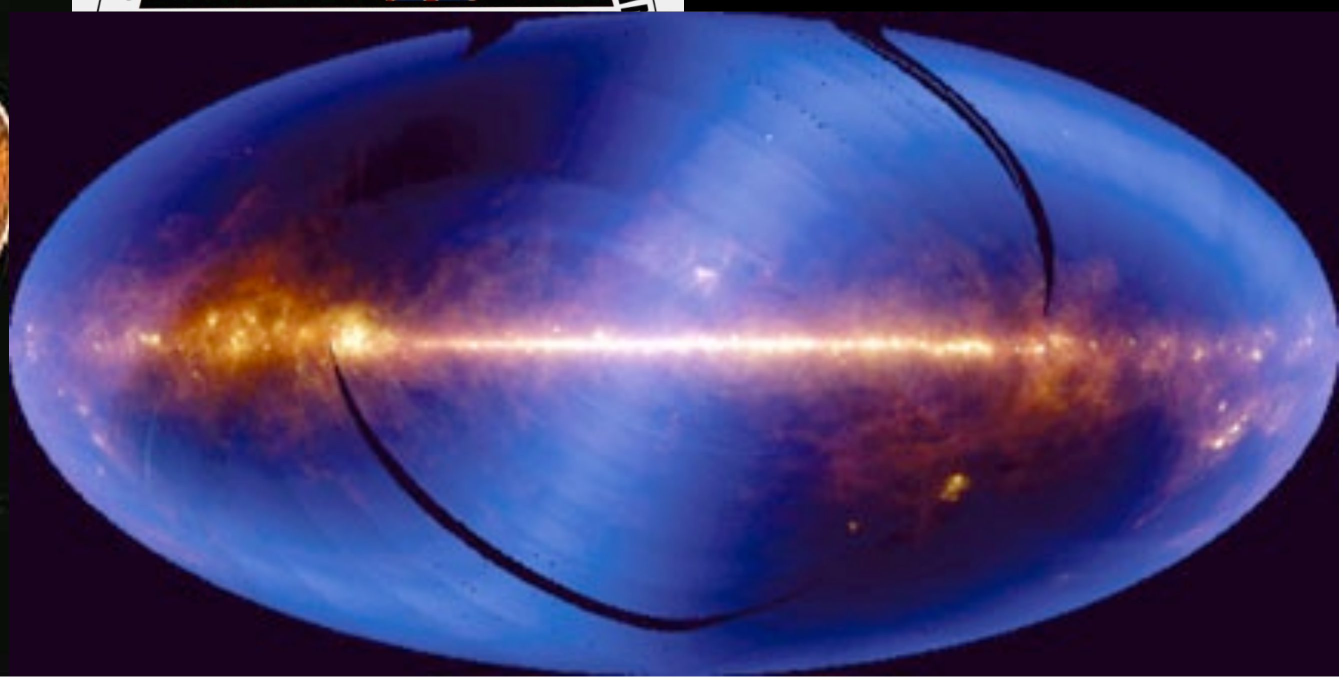


Myers, Benson and Wright, 1984, ApJ, 279, 27

Meanwhile, on the West Coast, the infrared world was about to change forever

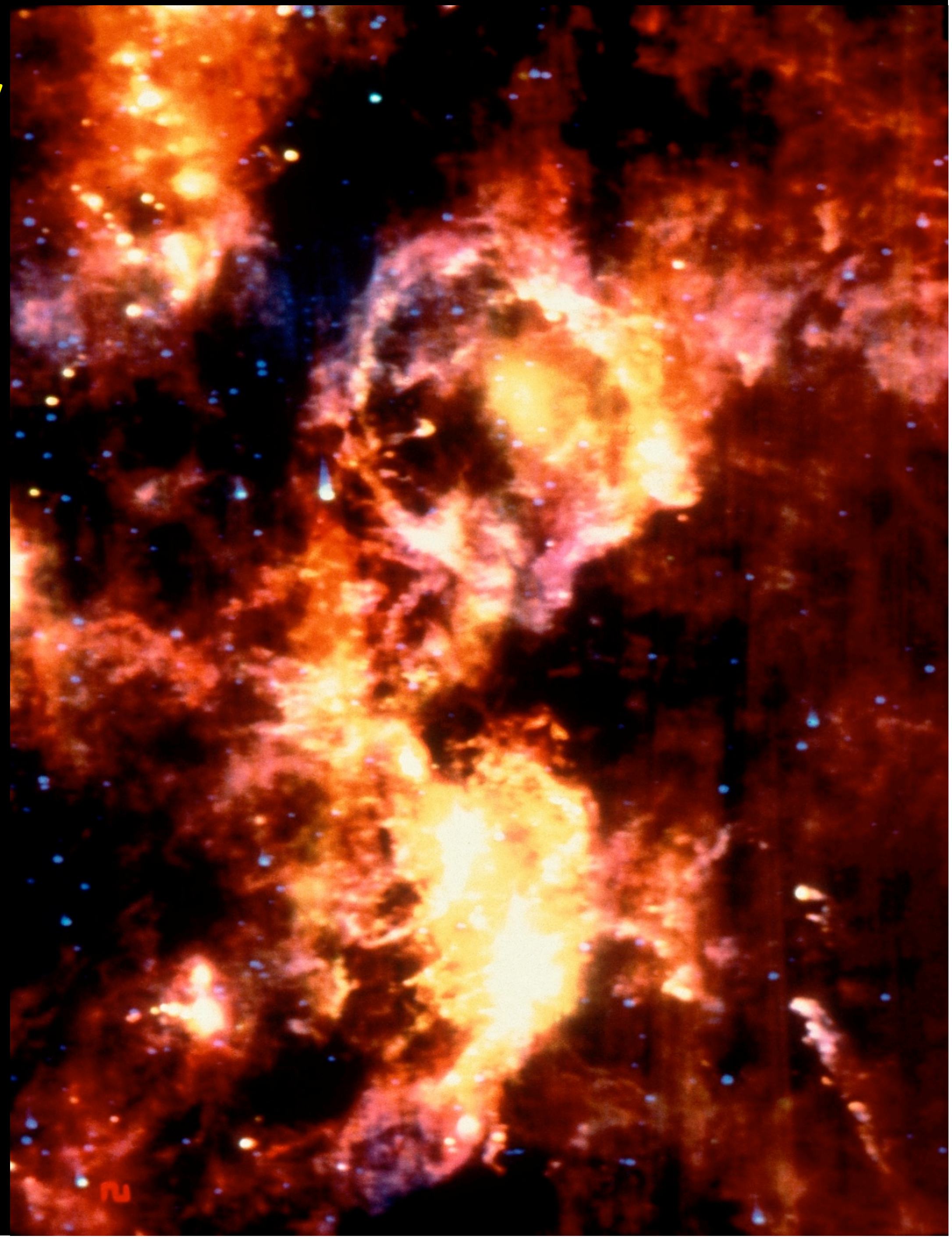
IRAS Launches On Jan. 26, 1983



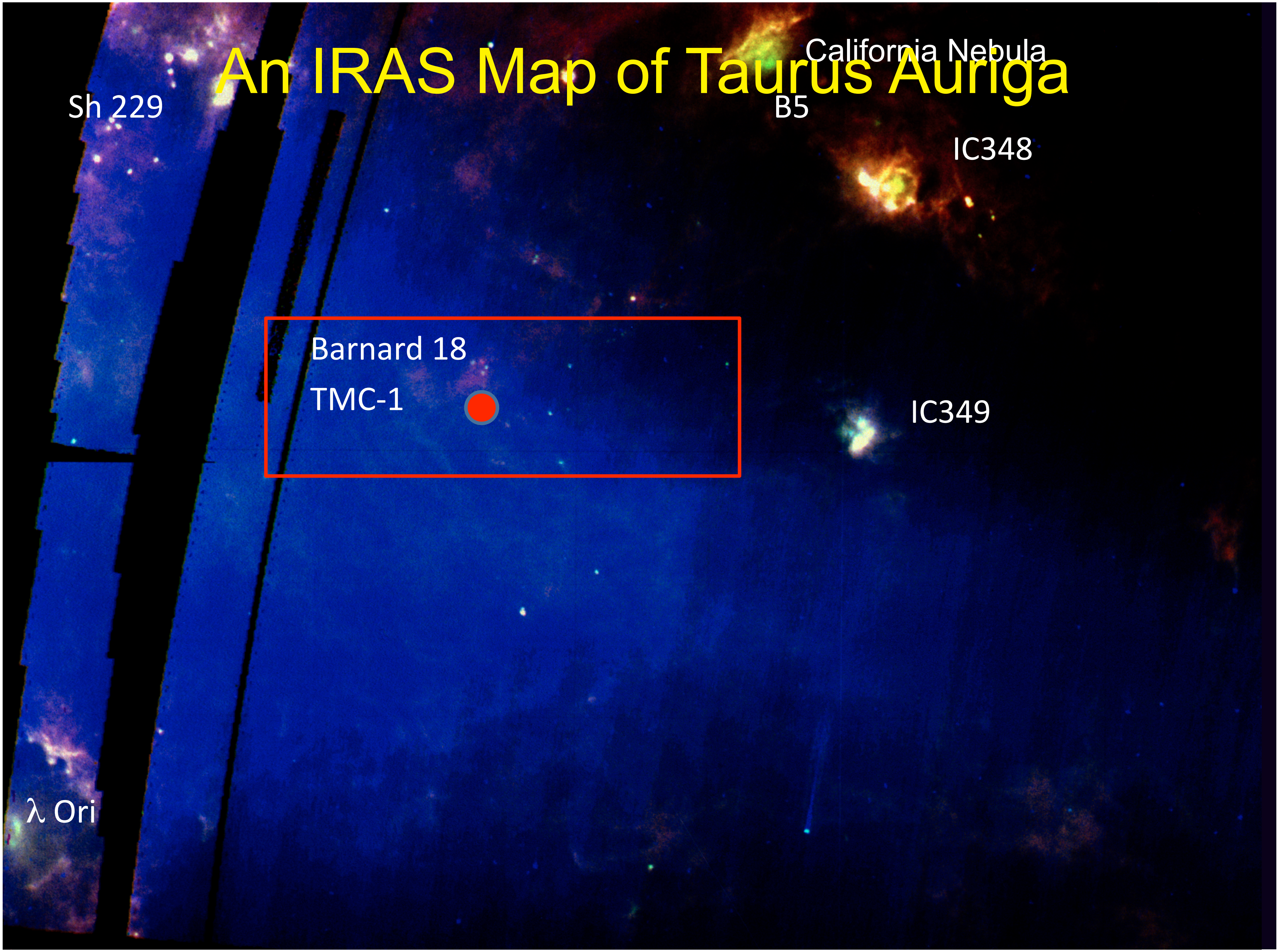


The IRAS Survey

- For 300 days, a cryogenic 60 cm telescope surveyed >95% of sky at 12, 25, 60 and 100 μm
- IRAS found > 600,000 discrete objects ranging from solar system objects and stars, to molecular clouds and distant galaxies
- Star formation would never be the same



An IRAS Map of Taurus Auriga

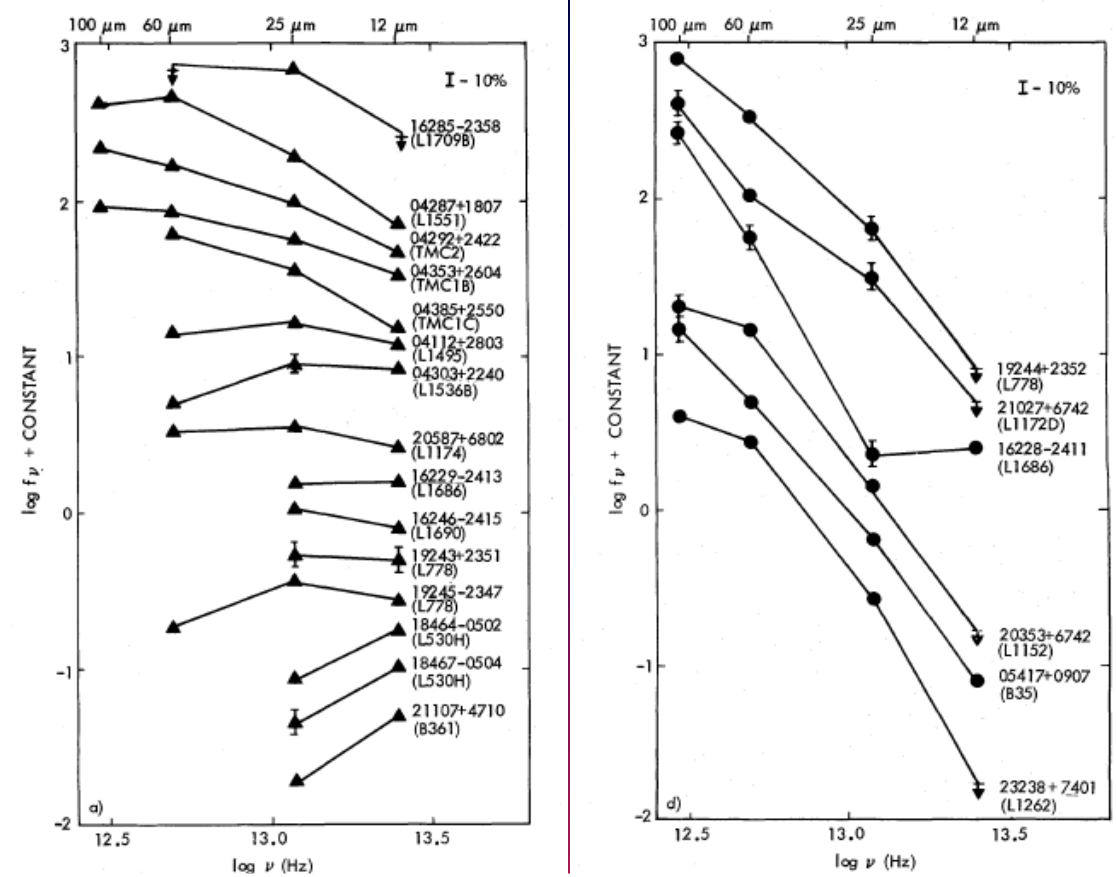


IRAS Dense Cores Program

- IRAS Mini Survey passed across B5 leading CAB and PCM to get in touch.
- Targeted ~100 dense cores (Myers & Benson 1983) into a high sensitivity pointed program with IRAS
- The search for embedded sources was on!
- 35 of 78 cores had IRAS sources with $1<L<10\ L_o$
- Sources with NO visual counterpart were colder (190 vs 240 K) and closer to core (0.01 vs. 0.19 pc)
- Cores with embedded IR sources more massive (1 vs. 0.4 M_o) and had broader linewidths (0.4 vs. 0.3 km/s)

Properties of IRAS Cores

- Broad range of SEDs suggesting broad range of temperatures
- Most SEDs (esp B5) inconsistent with central object heating spherical gas cloud.
  - Star + few 100 AU disk + envelope

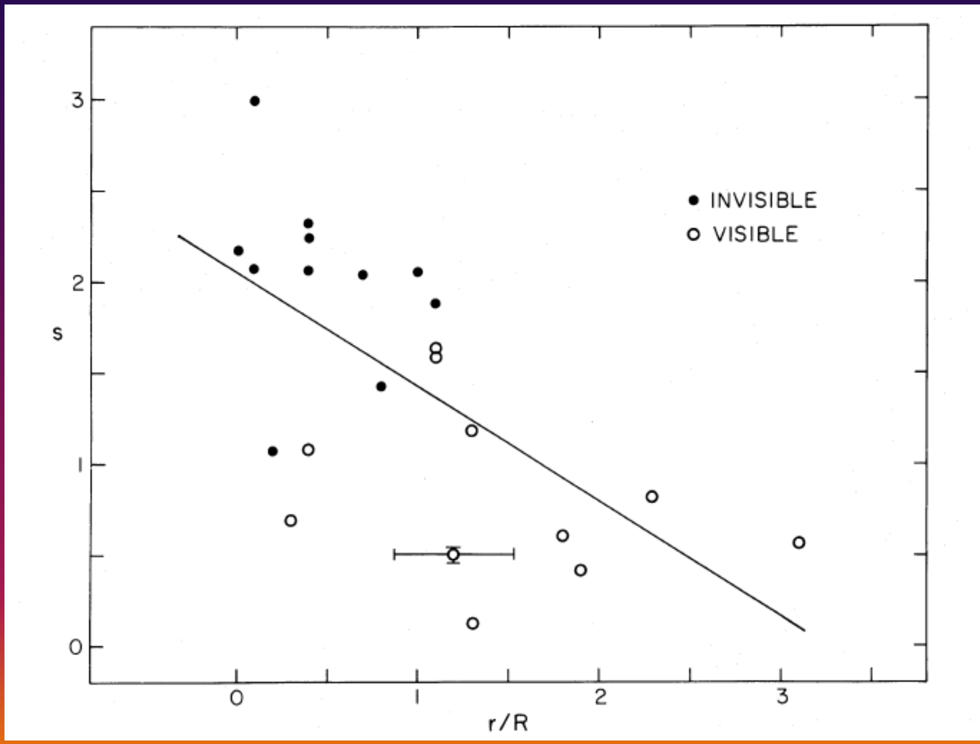


Beichman, Myers et al. 1986, ApJ, 307,337

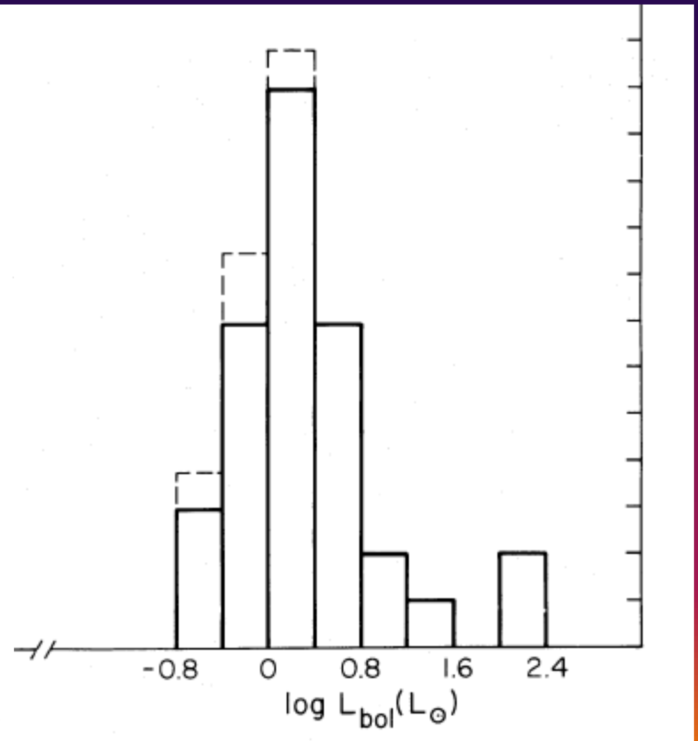
new view might involve a combination of steady accretion, perhaps through a disk, onto a slowly contracting star with mass outflow proceeding out of the poles of the system.

Properties of Embedded Sources

• Ground-based IR observations (Myers et al 1987) refined positions, added near-IR to permit complete SEDs for luminosities & detailed modeling



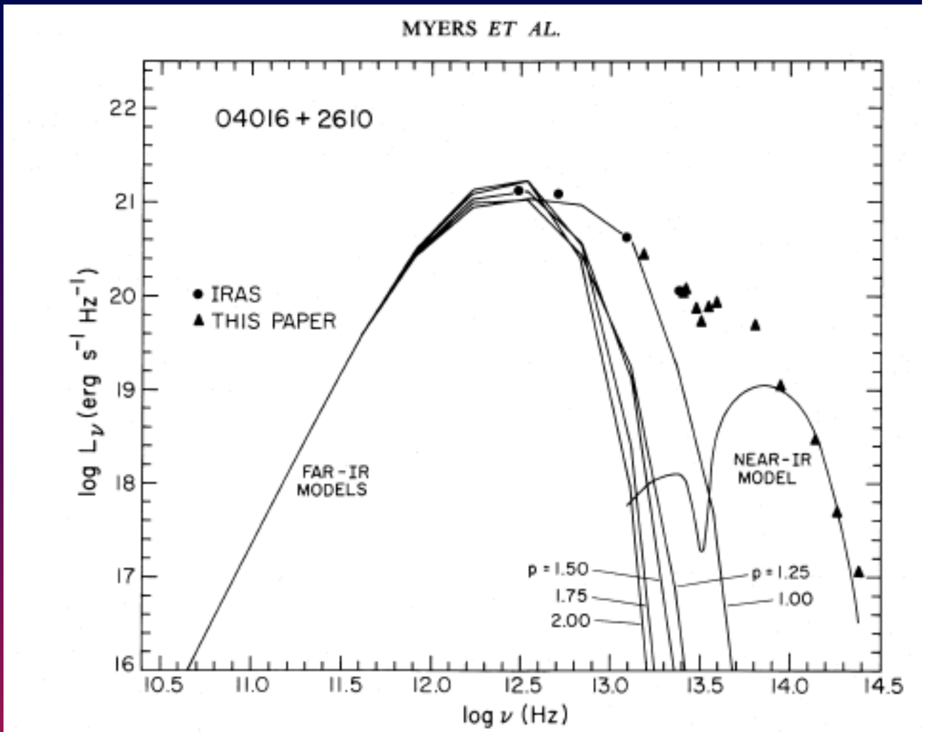
Invisible sources closer to core with steeper 2.2-25 μm slopes



Complete SEDs lead to luminosities of 0.1 to 10 L_o

Model For Embedded Sources

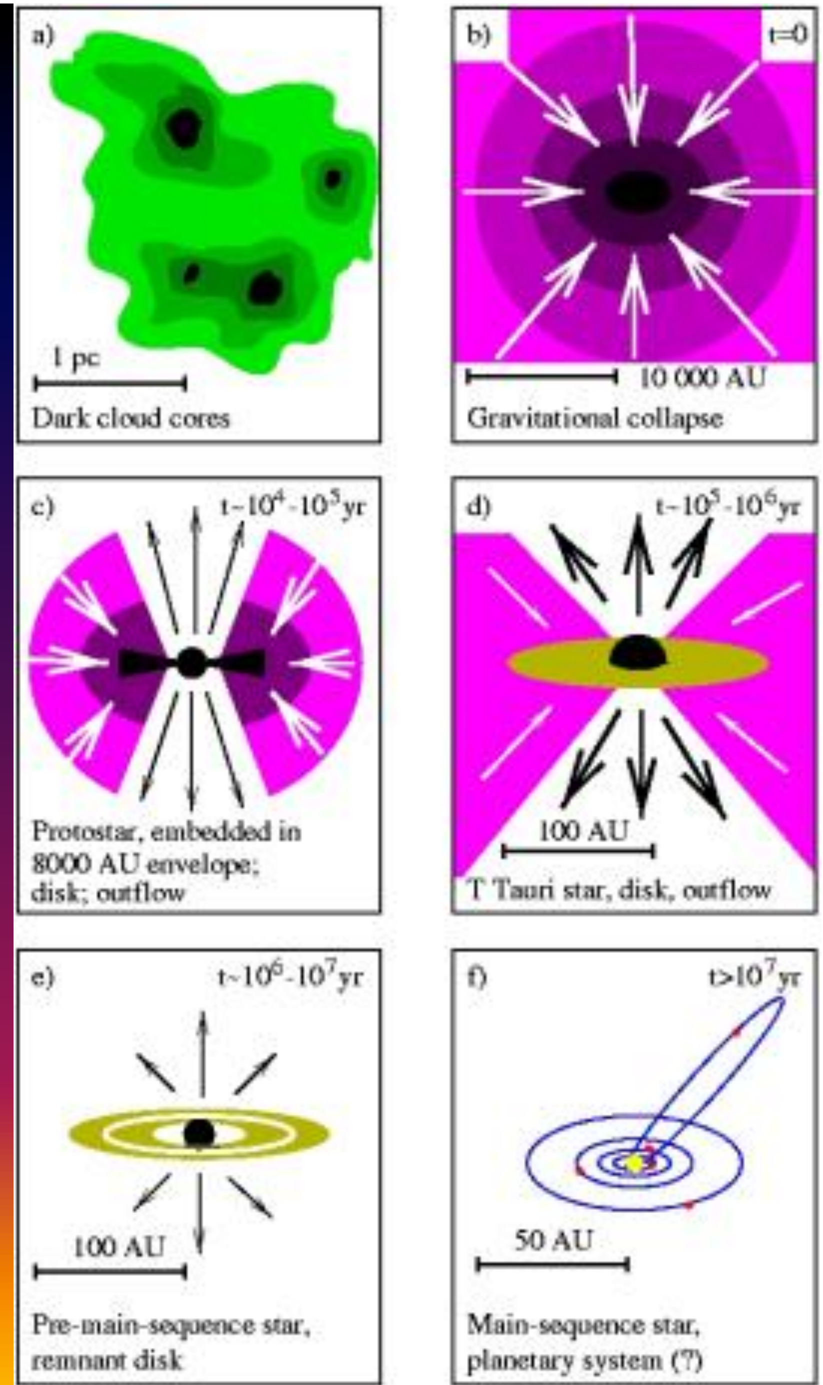
- Near-IR data suggest stars with T ~ 3000 – 6000 K + A_V~30 mag
- Far-IR data suggest dust heated by central star out to few 100 AU
- Consistent model fits near and far-IR, but NOT mid-IR
- Missing emission could arise from disk within cavity of central <100 AU (Adams, Lada, Shu 1987, ApJ, 312,788)



"Near-infrared And Optical Observations Of IRAS Sources In And Near Dense Cores" --- Myers, Fuller, Mathieu, Beichman, Benson, Schild, Emerson 1987, ApJ, 319, 340 --- Phil's #2 paper with 362 Citations

IRAS Dense Cores Validate Star Formation Paradigm

- Dense cores form stars
  - 50% of cores have IRAS sources
- Obscured stars become TT stars
  - Similar 1-2 L_o luminosities and Teff
  - Co-located in or near clouds
  - Time scale for revealing obscured objects ~10^5 yr
- Obscured stars have disks
  - Explain missing mid-IR
- P.S. Planets are natural outcome, but that is a story for another decade!



Hogerheijde 1998, after Shu et al. 1987

The Best Is Yet to Come

- Observations and theory have added layers of sophistication
  - HST proplyds with ~500 AU disks
  - MM interferometers & Keplerian disks
  - KI/VLTI/CHARA probe central AU of gas and dust disks
  - Spitzer and other telescopes have extended census of young stars/ planets to Jupiter masses
- Much more to come: WISE, ALMA and JWST with possibly SIM in the future