Outlook and Future Challenges in Stellar Radio Astronomy

Sun Kwok

Haystack, October 5, 2012

Historical motivation

- Radio stars: radio emission from optical point sources which are not extragalactic
- Peculiar stars such as AG Peg, LkHa 101, MWC 349, HM Sge, V1016 Cyg, Hb 12, HR 1099, CH Cyg
- Do not have typical thermal spectrum: intermediate spectral index

History

Single or binary?

flares

- First radio star workshop: June 1979, in Ottawa, Canada (over 30 years ago!)
- Topics covered: RS CVn, emission-line stars, novae, symbiotic stars ([Be] stars), binary stars (a mixed bag of objects)
- Technique: single dish radio telescopes at cm wavelengths (flux vs. wavelength)

Confusion, no spatial information

Circumstellar nebula, stellar ejecta (including compact PN)

Stellar environment

- Photosphere, star spots
- Chromosphere, corona, coronal mass ejection, stellar winds
- Non-uniform temperature and density
- changing degree of ionization with position
- Molecular and solid states of matter
- Binary systems: accretion disks

Radiation mechanisms

- Non-thermal radiation: synchrotron radiation from SNR
- Thermal free-free emission: circumstellar nebulae photoionized by a central star
- Masers: OH, H_2O, SiO
- Plasma radiation (Sun and active stars)
- Molecular lines: rotational lines in the mm/subm
- Dust continuum (in the submm)

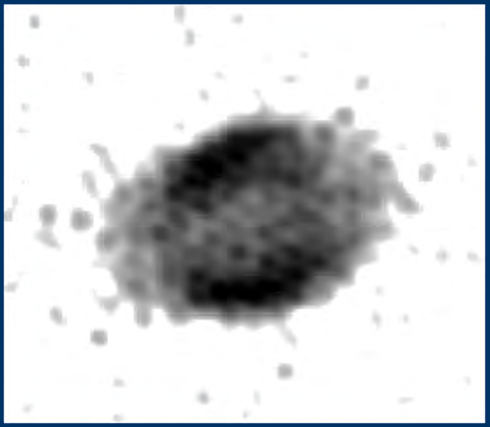
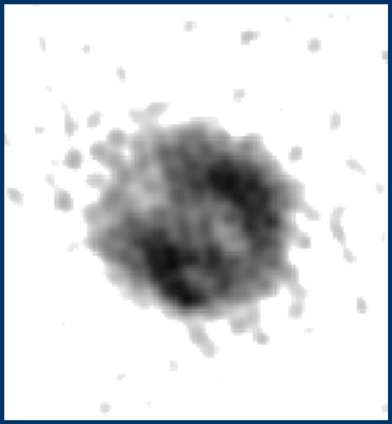
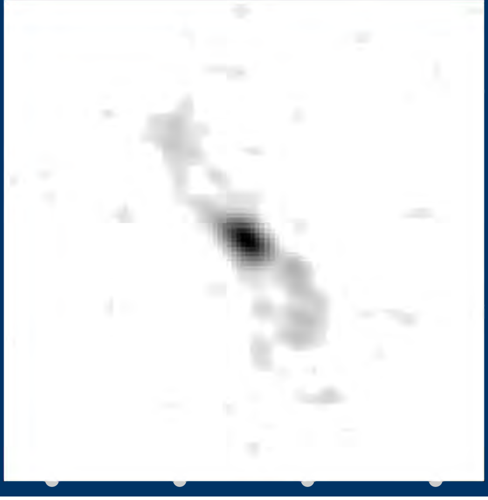
Circumstellar nebula

- Requires a mass supplier and a source of photoionization
- Stellar wind from RG star photoionized by an exposed hot core (young PN) or a companion WD (symbiotic star)
- Subarcsecond resolving power provided by the VLA in early 1980s, exceeding those of optical telescopes

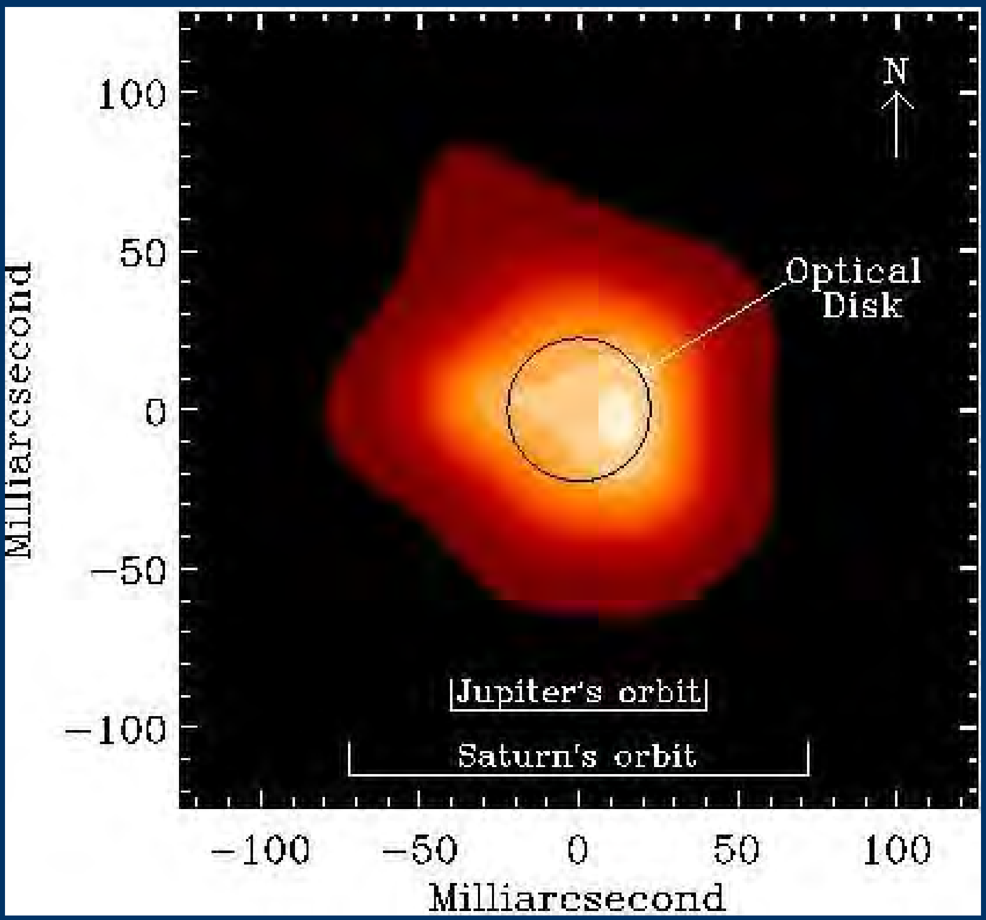
"star": optical point source

Radio "stars"

- With the *Very Large Array*, we were able to image many young planetary nebulae that are too small to be resolved by optical telescopes

Continuum imaging of stellar surface



VLA (Lim et al. 1988)

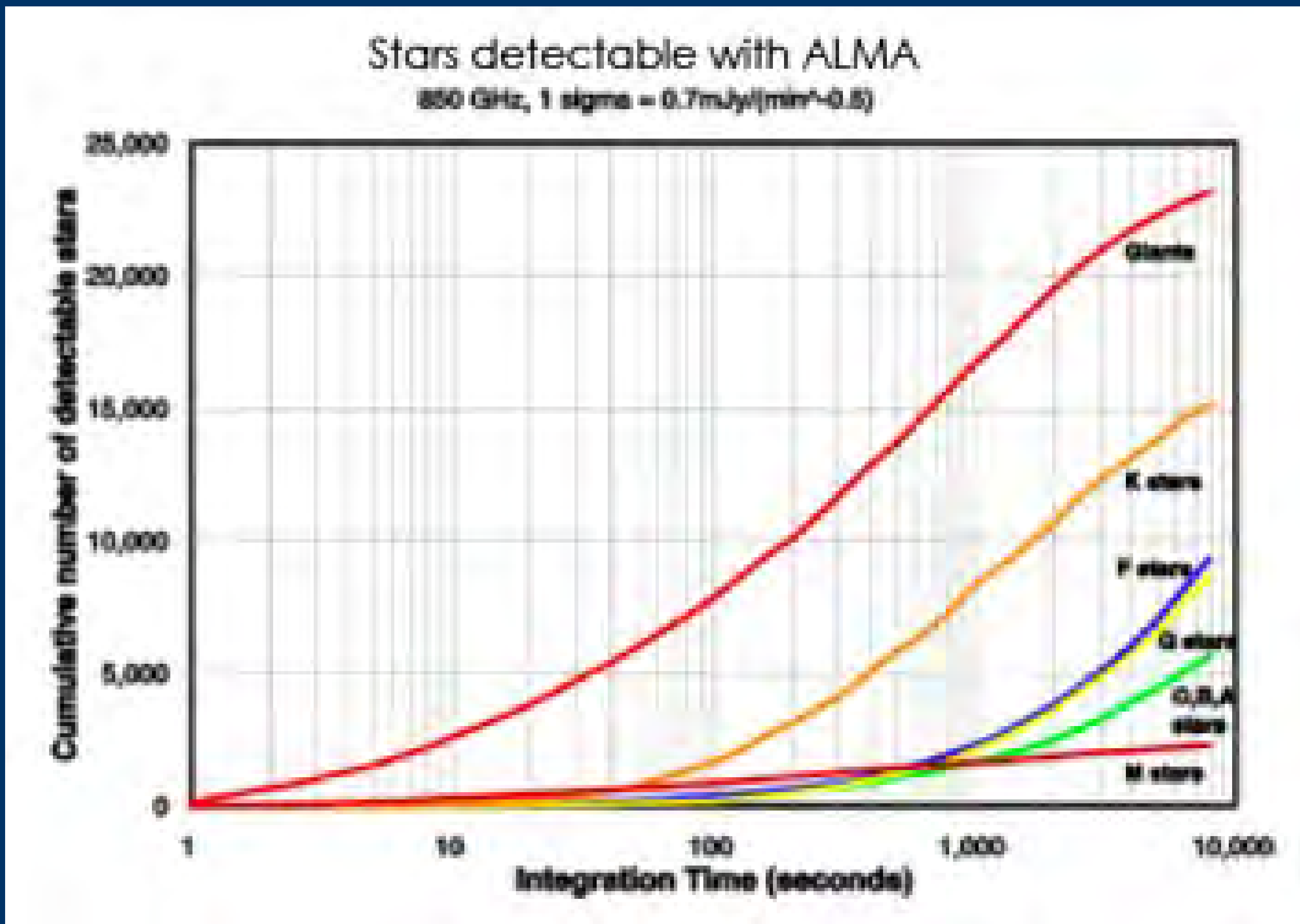
Now seen in α Tau and α Boo (O'Gorman) with JVLA

α Ori also observed by MERLIN (Richards)

NML Cyg (VLA, Zhang), IRC+20216 (JVLA, Menten)

- *Can learn from the Sun! (*White, Bastian*)*
- *Transient phenomena (*Osten*)*

ALMA


Stars detectable with ALMA
25,000
20,000
15,000
10,000
5,000
0
Cumulative number of detectable stars
1
10
100
1,000
10,000
Integration Time (seconds)
Giants
K stars
F stars
G stars
O,B,A stars
M stars

Current and future improvements

- Frequency coverage: from cm to mm and submm wavelengths (PdBI, SMA, CARMA, etc).
- Spectral line and imaging modes
- Angular resolution: interferometers (VLA, VLBI)
- Increased sensitivity and dynamical range: larger bandwidths (JVLA, eMERLIN), larger and more antennas (ALMA)
- Dynamic imaging spectroscopy: MWA (Oberoi, Bastian)

Science goals

- Morphology
- Physical conditions (temperature, density, radiation background, magnetic field)
- Kinematics: expansion, precession, spiral
- Chemistry: distribution, C-rich vs O-rich, time evolution

Thermal free-free

$$F_\upsilon \propto \upsilon^{2/3} \left\{\frac{\dot{M}}{V}\right\}^{\frac{4}{3}} D^{-2}$$

- Intermediate spectral index indication of mass loss (Güdel)
- Winds from OB stars: radiation pressure on resonance lines
- Determination of mass loss rates

The detection of mass loss from OB and WR stars was key to the development of stellar evolutionary models of massive stars

Multi-frequency lightcurves

- Radio monitoring of novae and symbiotic stars allow precise determination of mass loss history
- f-f opacity decreases with frequency
- Shrinking radio "photosphere" determines changing mass loss rate with time (Kwok 1983, 1984).
- Now can be imaged by VLBA (Mioduszewski)

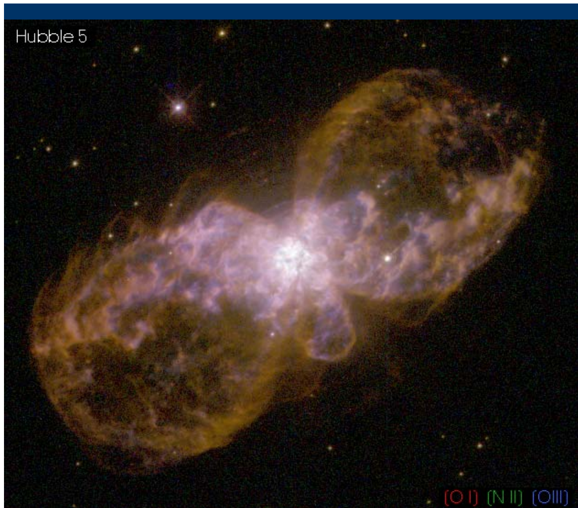
Complete spectral coverage

- Nature of classical novae understood as the result of UV photometric observations
- Optical light curve only correctly interpreted after UV and infrared observations available
- Now we have access to radio, x-ray, gamma ray (Rupen, Chomiuk)

Fast winds from CSPN

- The identification of radiation pressure on resonance lines as the mechanism of driving mass loss from OB stars (Crammer) suggested that hot central stars of planetary nebulae also have stellar winds
- The interaction of these fast ($\sim 10^3$ km/s) wind with the slow wind of the AGB progenitor leads to the formation of PN

The interacting winds process is also responsible for shaping of PN



Bipolar and multipolar nebulae are common (Sahai)

Bipolar morphology already present in proto-PN

The Silkworm Nebula

The Cotton Candy Nebula

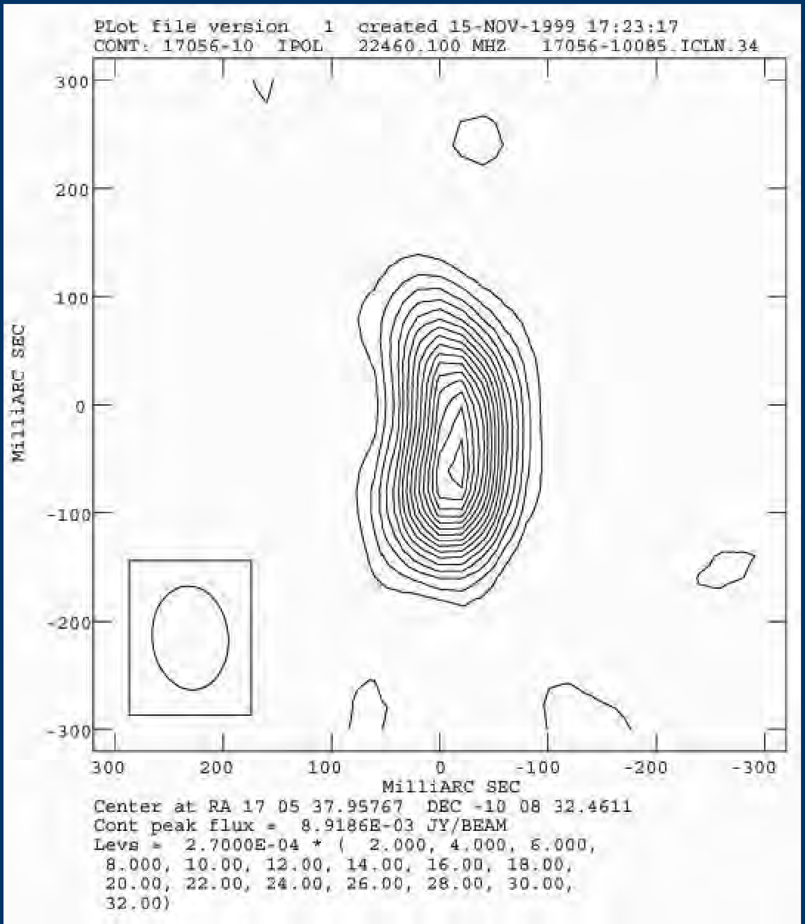
The Walnut Nebula

The Water Lily Nebula

The Spindle Nebula

Reflected starlight, not emission!

Collimated fast outflow



Bipolar and multipolar lobes shaped by collimated fast outflows from central stars?

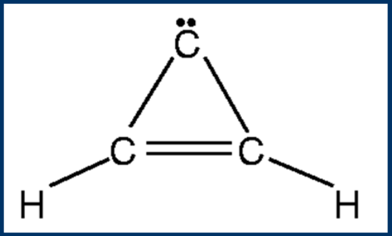
Lim & Kwok 2003, Lee, Lim & Kwok 2007

Stellar collimated outflows

- Young stars: Wolk
- White dwarfs: novae, symbiotics (Sokoloski)
- Outflow direction perpendicular to binary plane: driven by accretion disk? Lessons for x-ray binaries and AGNs?

Evolved stars as molecular factories

- Rotational transitions of over 60 molecules have been detected in the circumstellar envelopes of AGB stars
- Inorganics: CO, SiO, SiS, NH_3, $AlCl$, ..
- Organics: C_2H_2, CH_4, H_2CO, CH_3CN, ..
- Radicals: CN, C_2H, C_3, HCO^+
- Rings (C_3H_2), chains (HC_9N)

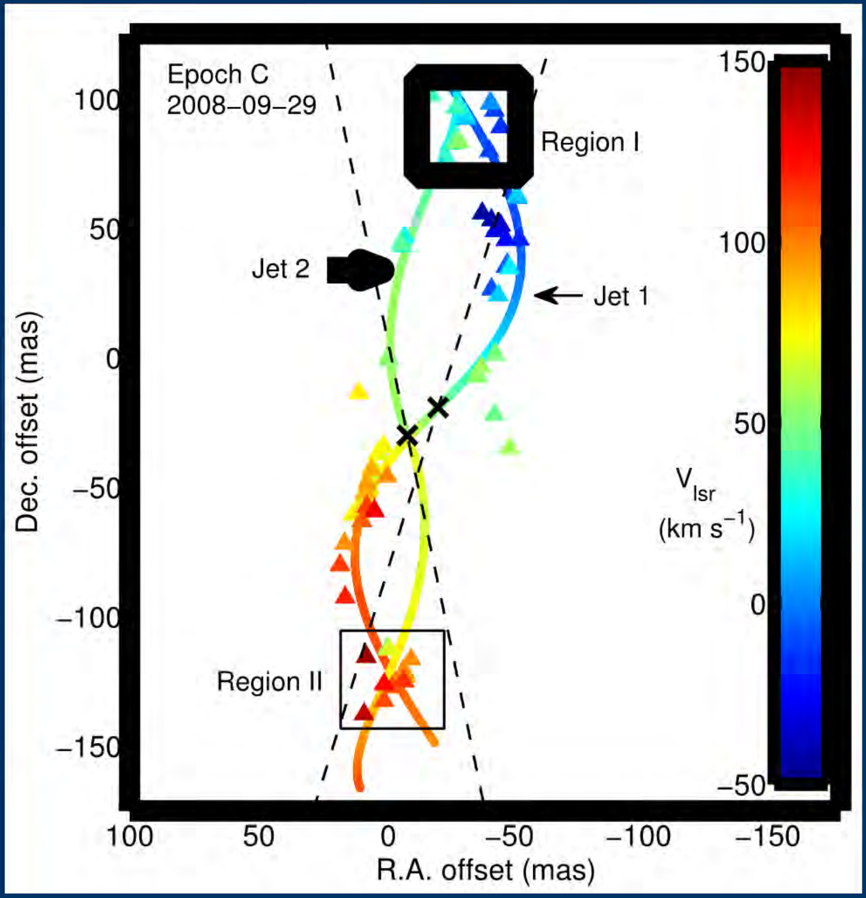


Molecular line observations in the cm wavelength range

- Rotational (maser) line of H_2O at 1.3 cm and the Λ doublet line of OH (18 cm)
- Inversion line of NH_3
- Rotational lines of heavy molecules such as cyannopolynnes (HCN, HC_3N, HC_5N, etc.)

Masers as kinematic tracer

- Jets from water fountain (Deguchi)
- Precessing motion: driven by binary motion?
- Magnetic driven? (Vlemmings, Amiri)
- Tracers of spiral and galactic structure (Reid)

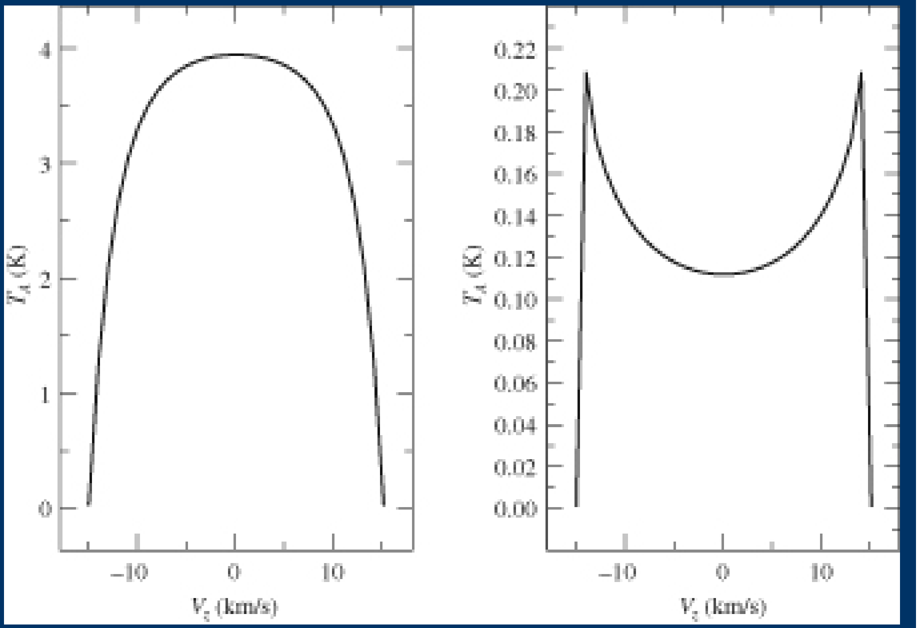


VLBI

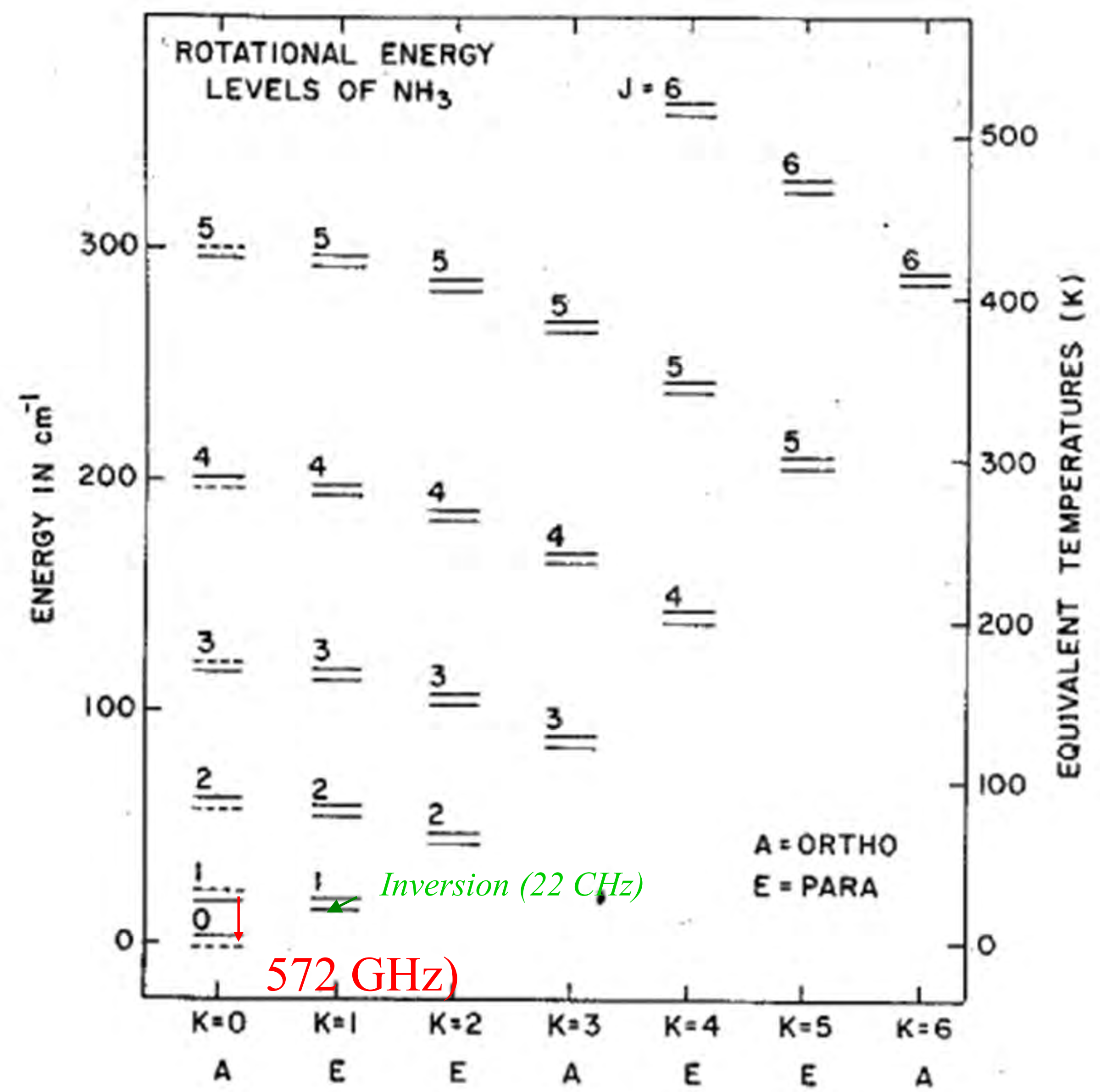
- Very high angular observations of high surface brightness emission regions
- Kinematic studies from maser observations
- Trigonometric parallax: distances to red giants and PN are difficult (Zhang, Choi, Melis)
- Loss of VLBA?

Molecules as probes of stellar winds

- double peaked OH masers as manifestation of mass loss from evolved stars ($\Delta V = 2V_{exp}$)
- Thermal CO emission: excitation temperature, density profile, velocity



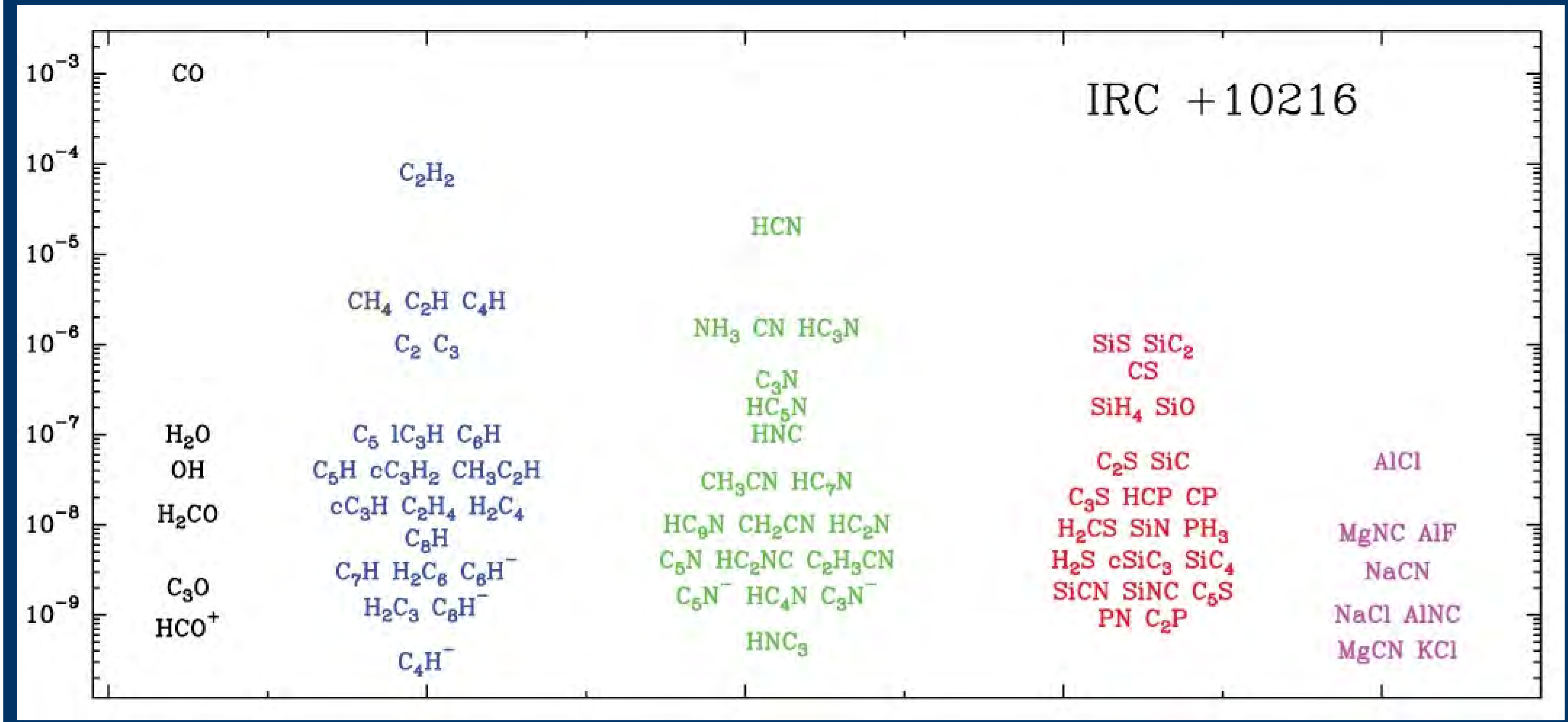
Line width: expansion velocity
Peak: excitation temperature
Profile: density law



IK Tau, OH231.8, IRC+10420 (JVLA, Menten)

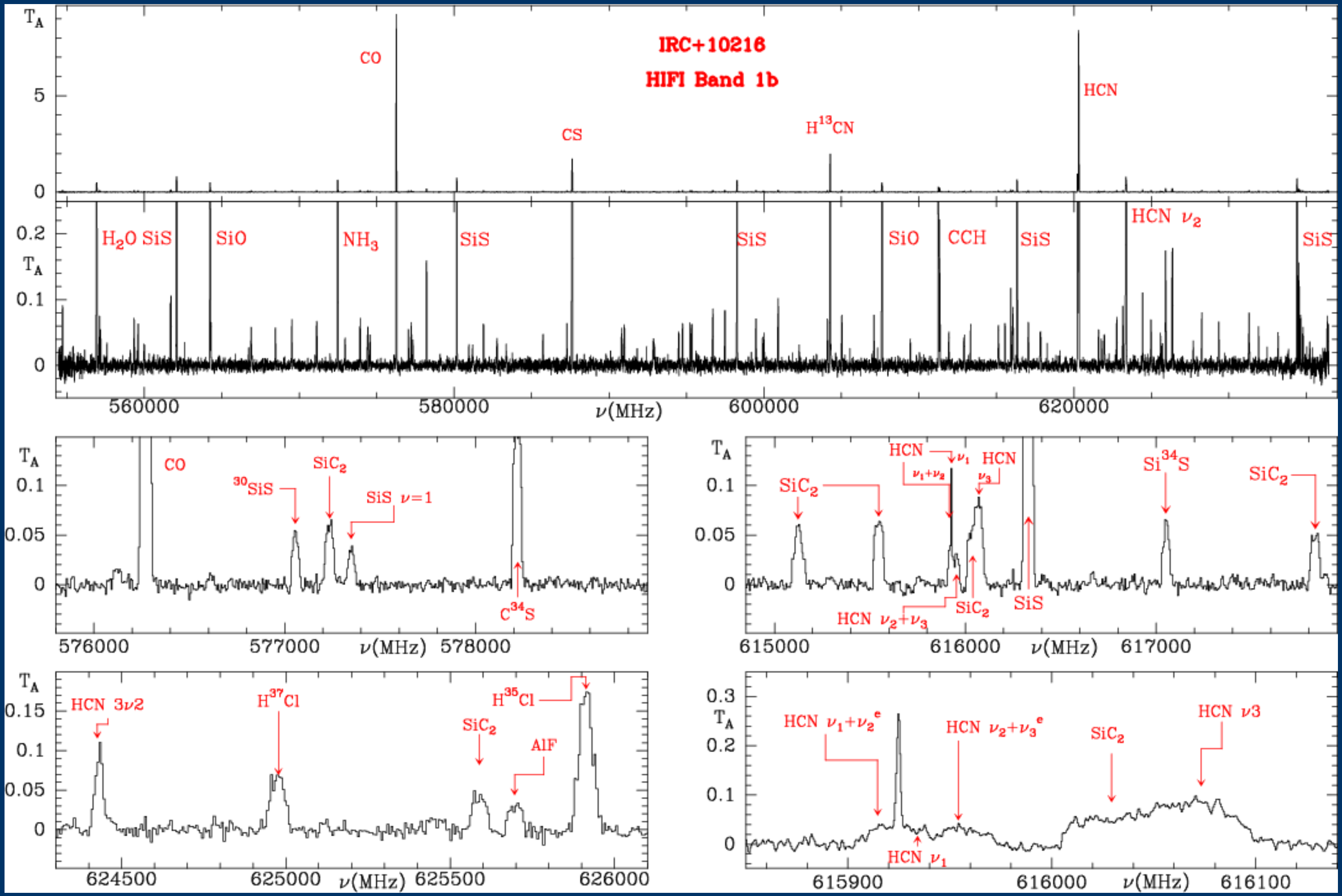
Detection of the 1-1 inversion line in IRC+10216 (Bell et al. 1982)

Molecular synthesis in AGB stars



Cernicharo et al. 2011

Herschel spectral line survey

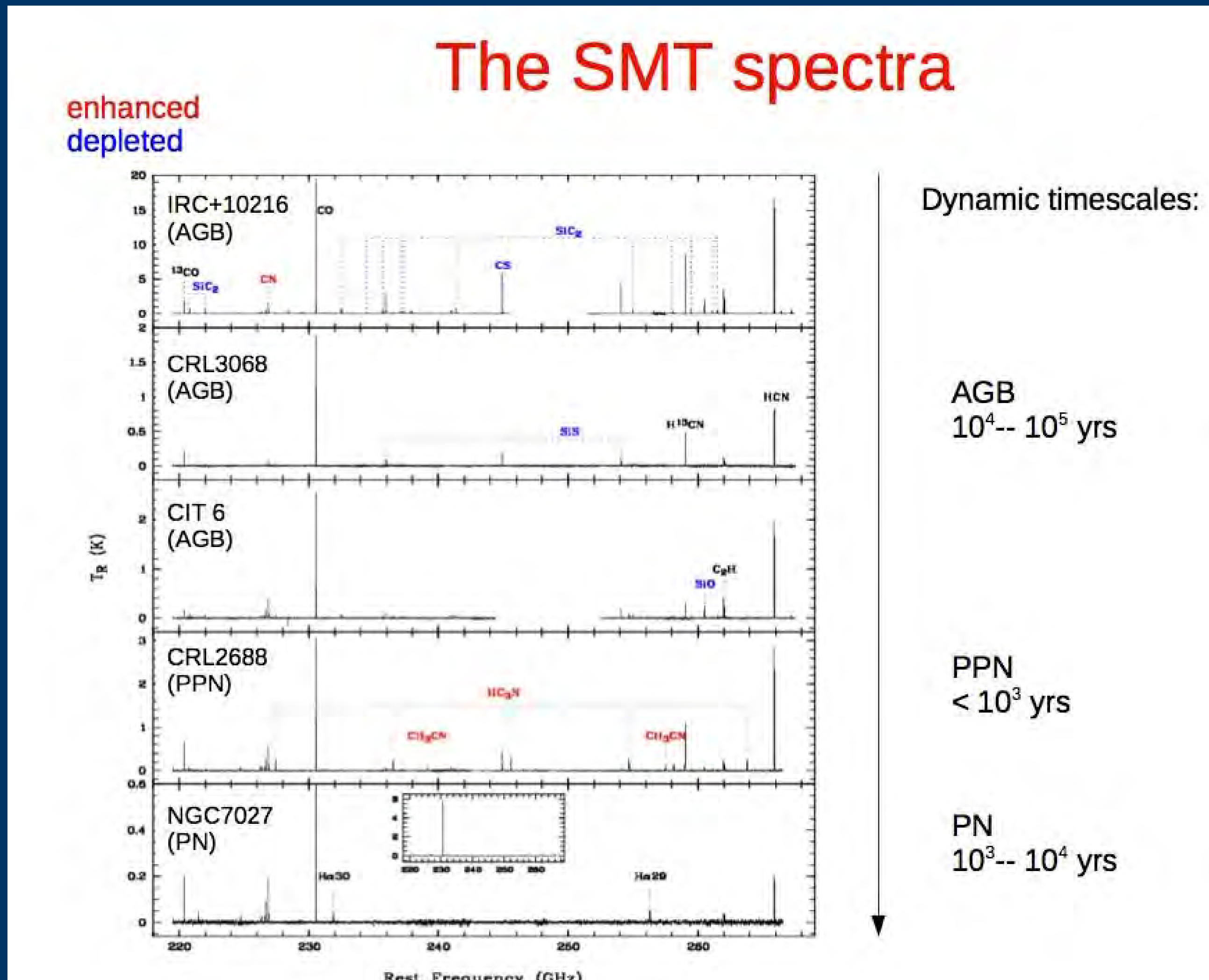


Stellar chemical synthesis

- A single energy source
- Well determined physical conditions: density, temperature, radiation background
- By comparing the molecular abundance at different stages of stellar evolution, one can constrain the chemical model of molecular synthesis

Chemical times scales constrained by dynamical and evolutariony time scales

Spectral evolution



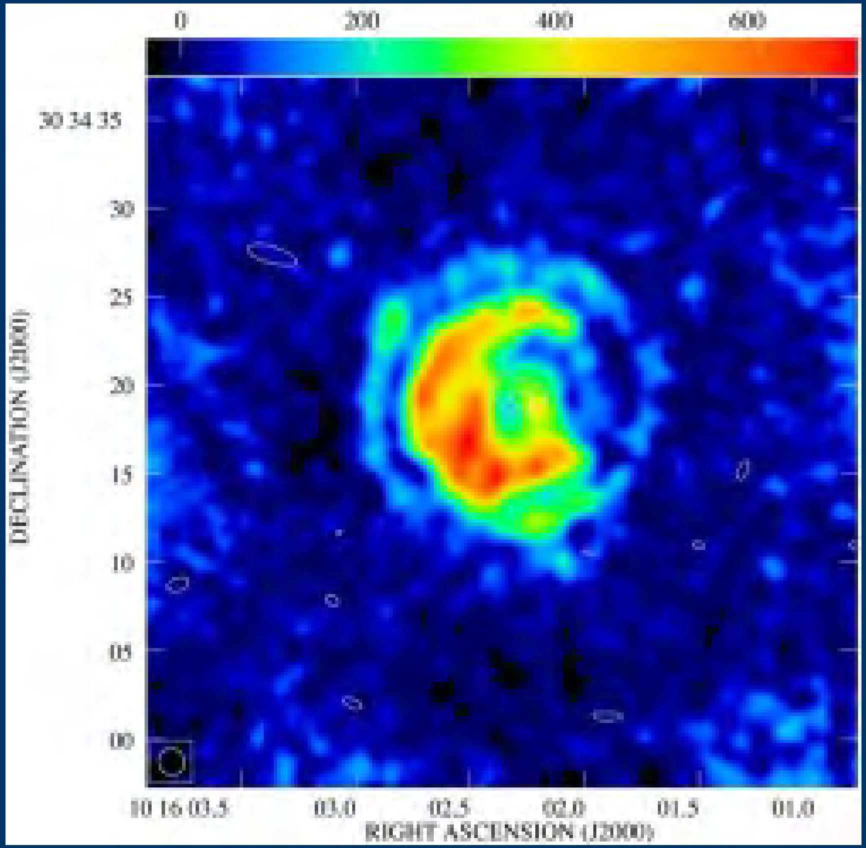
Chemical synthesis history

A new era of molecular line mapping

- VLA, SMA, PdBI, ALMA (Menten, Claussen, Young, Kaminski)
- Molecular formation history
- Kinematic structure
- Equivalent to integral field spectroscopy in the optical

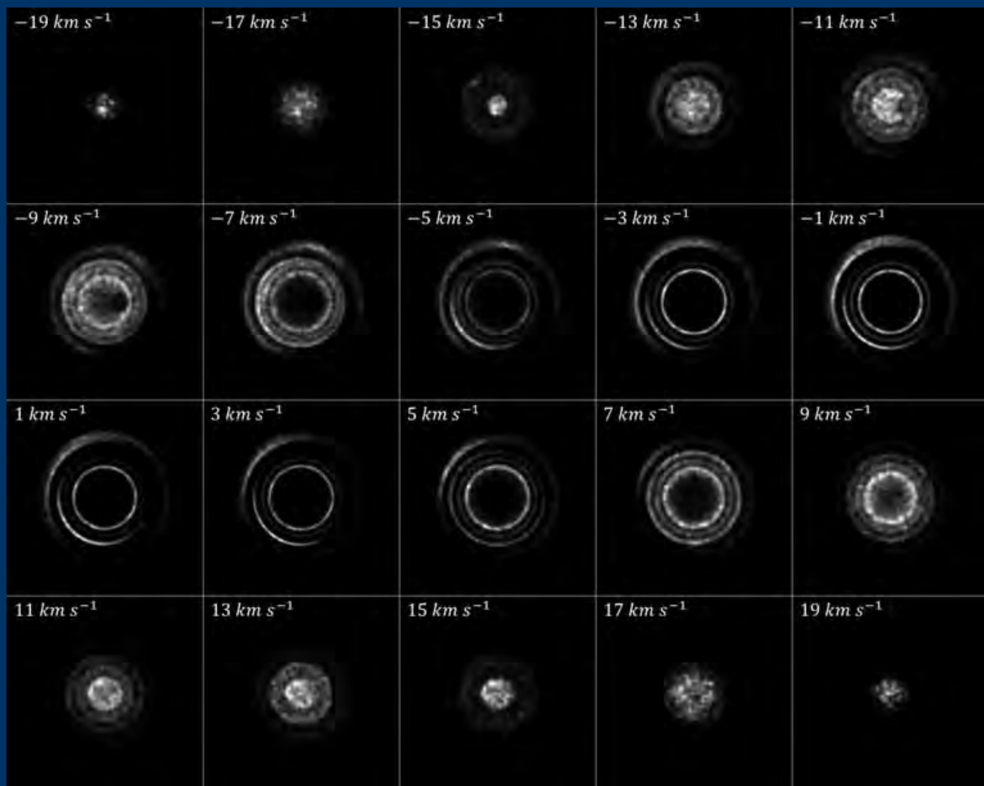
Line mapping with VLA

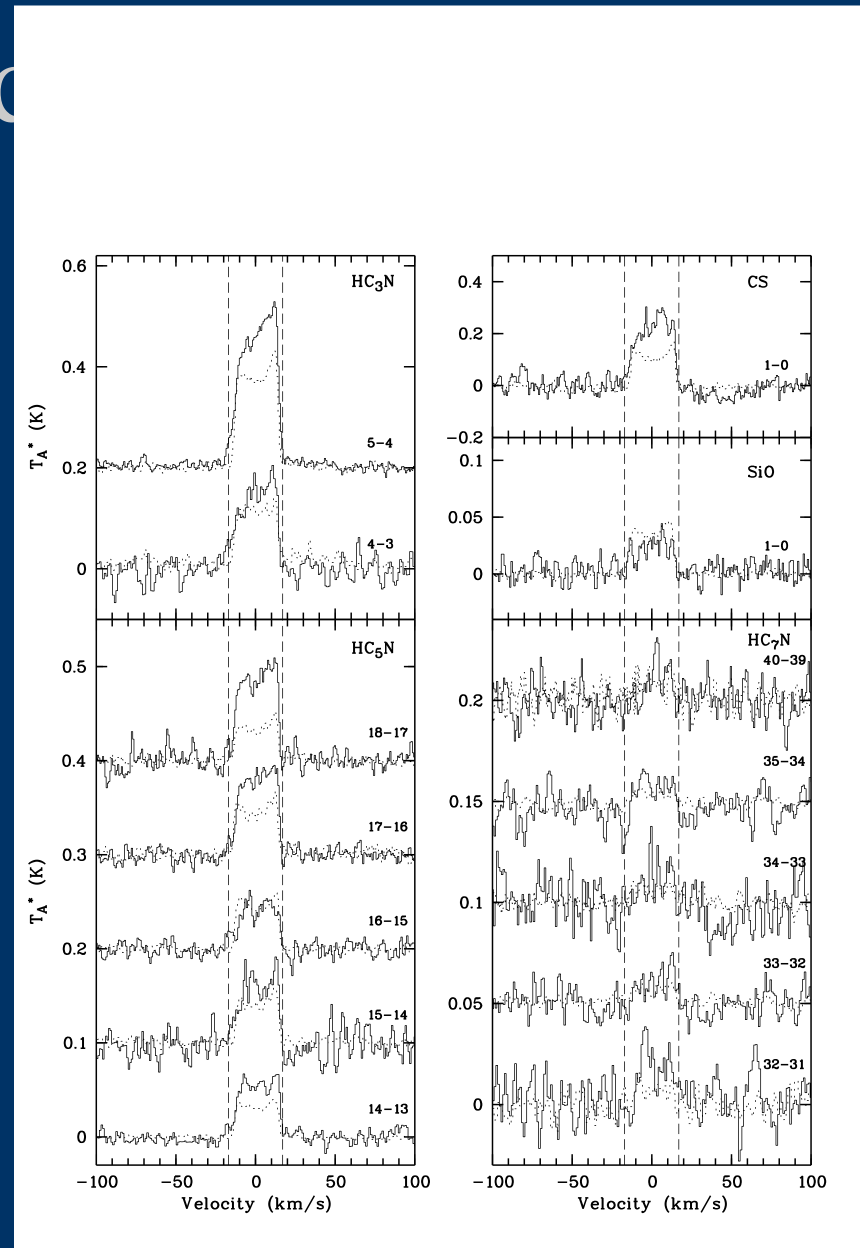
- HC_3N 5-4 line and 7 mm continuum map of CIT6
- Asymmetric, incomplete shells (spiral structure?)
- Anisotropic and episodic mass loss?
- Binary system?



Dinh-V-Trung & Lim (2009)
Sahai, Claussen (this conference)

3-D moc

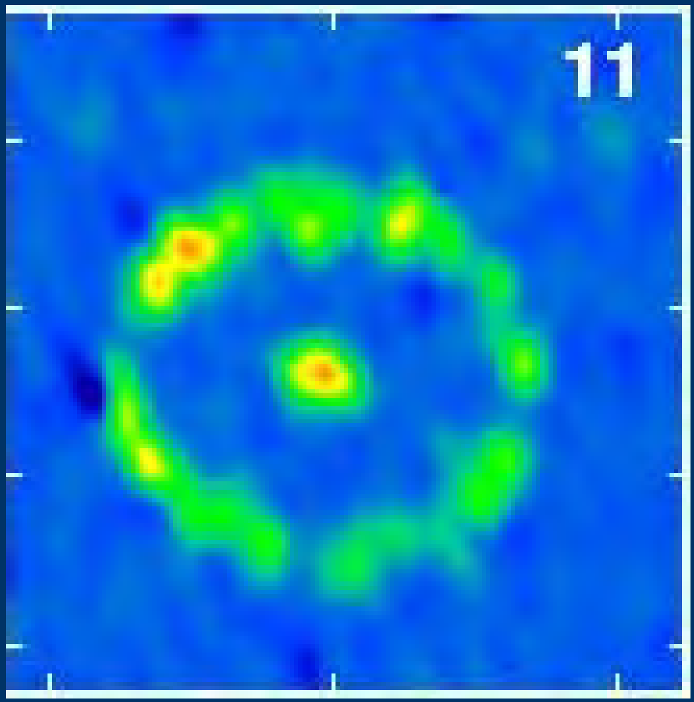




3-D model fittings of profiles and channel maps (Chau et al. 2012)

Mass loss history

- Detached thin shells: colliding winds or thermal pulse? (Maercker)
- Radio light curves: decreasing mass loss rate in nova and SN ejection (Rupen, Sokoloski, Chomisuk) (interaction with circumstellar materials)
- When did mass loss begin? (Le Bertre, Matthews)

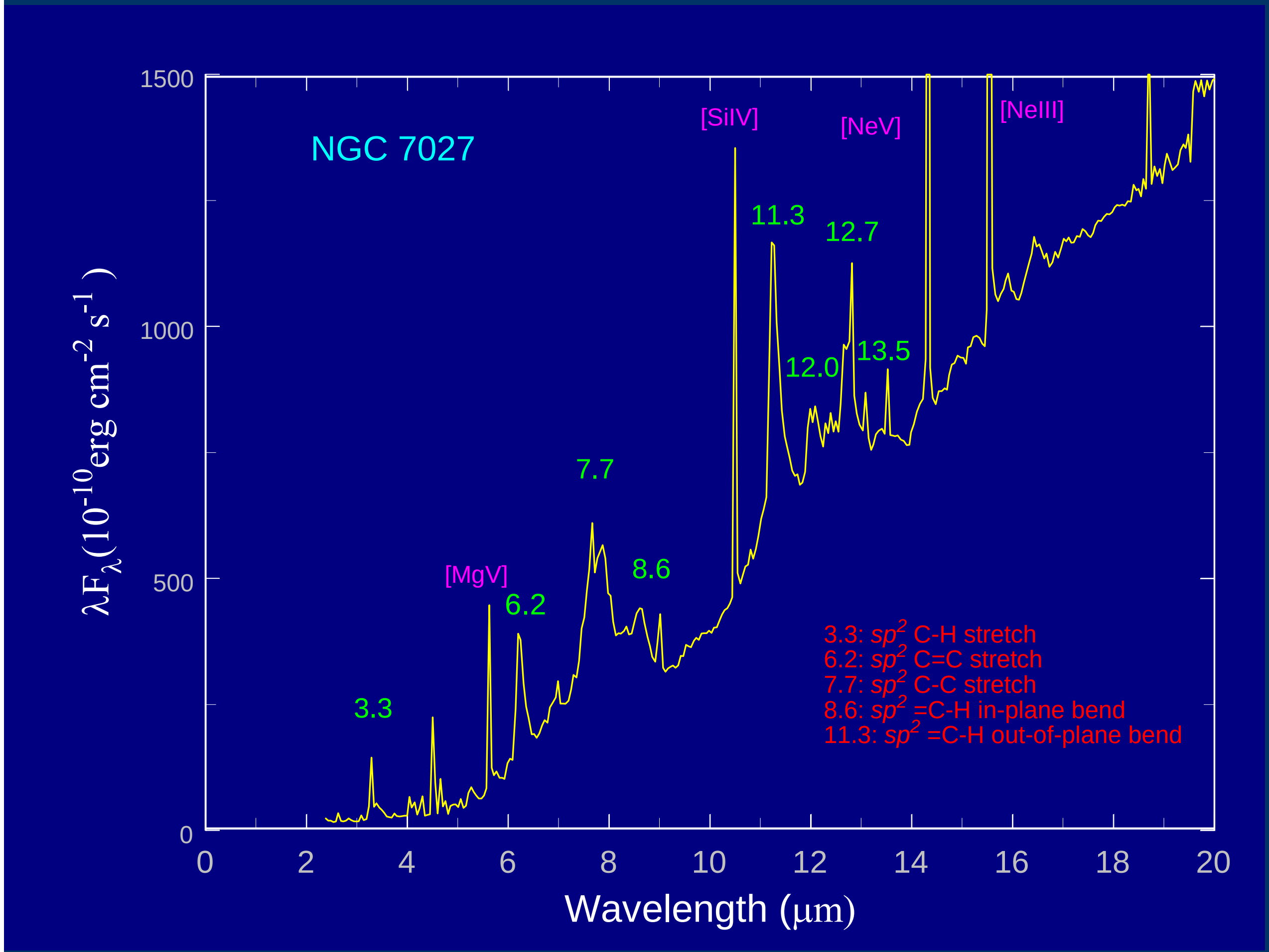


SMA map of R Scl
Note the sharp boundary

Circumstellar environment

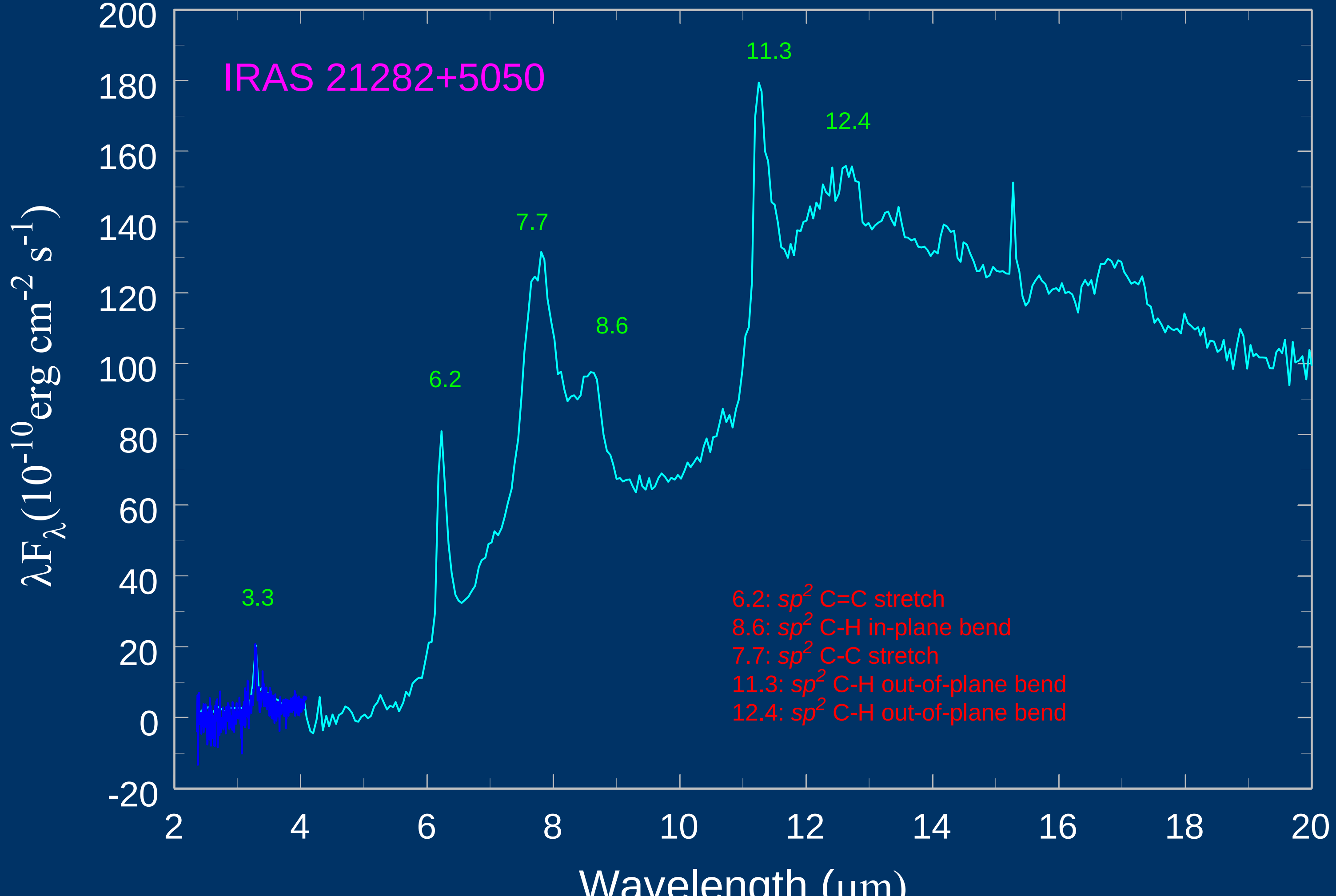
- Heavy elements dredged up from the core
- Formation of simple molecules (C_2, C_3, CN) in the atmosphere
- Circumstellar chemistry (HC_xN, C_2H_2)
- Condensation of solid-state grains
- Formation of aromatic and aliphatic compounds
- Photoionization of the gas component during the PN phase
- photochemistry

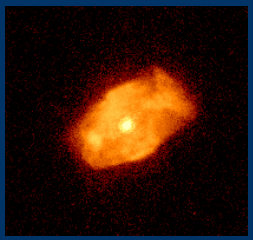
Unidentified infrared emission bands



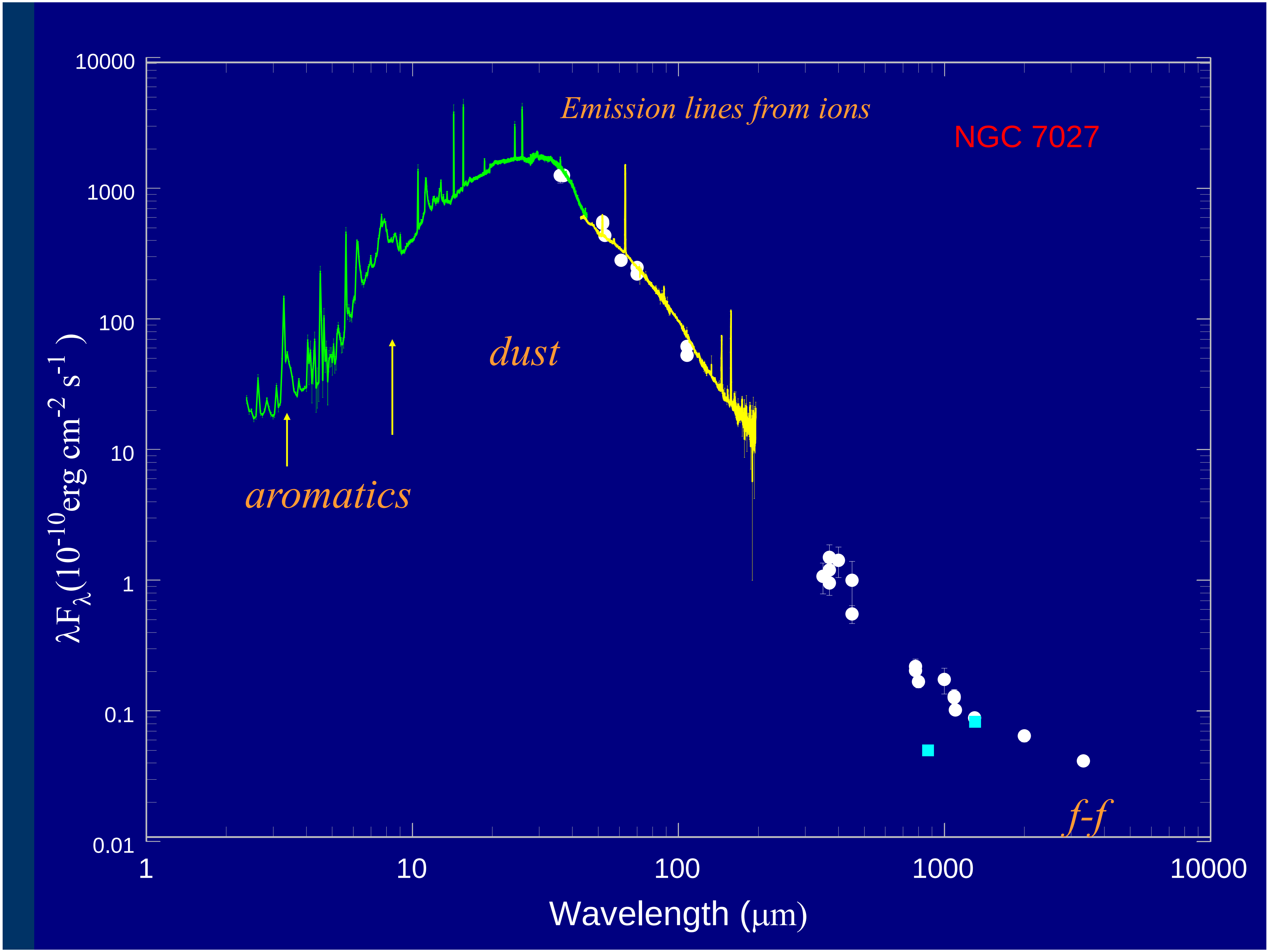
- 11.3 μm: Gillett et al. 1973
- 3.3 μm: Merrill et al. 1975
- 6.2, 7.7, 8.6 μm: Russell et al. 1978 (from KAO)

AIB are detected in many planetary nebulae. Since the carrier is synthesized in situ, PN are the best objects to study their origins





Mixed aromatic/aliphatic organic nanoparticles (MAON) Kwok & Zhang 2011, Nature, 479, 80

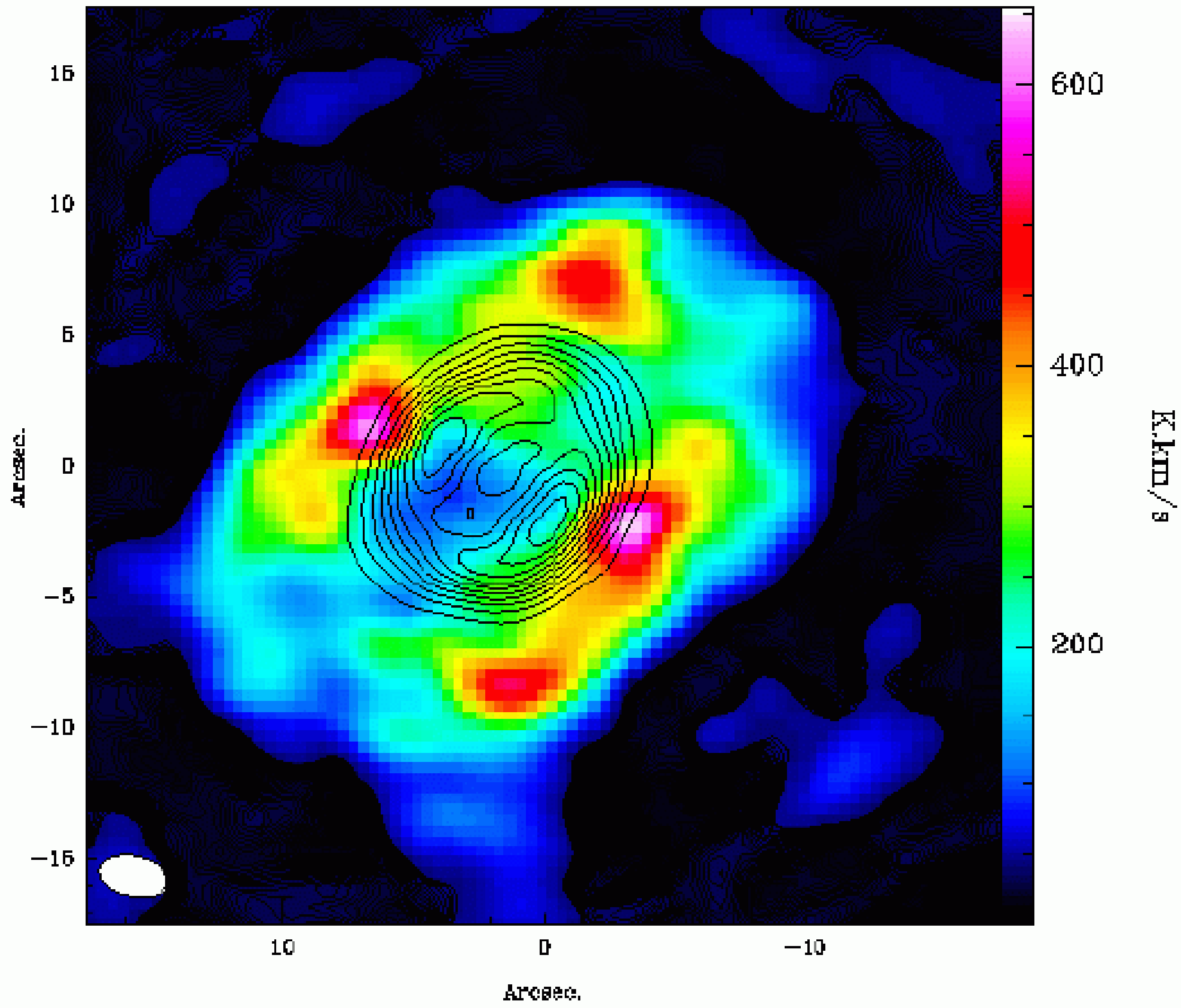


NGC 7027
Emission lines from ions
dust
aromatics
f-f
λF_λ(10^-10 erg cm^-2 s^-1)
Wavelength (μm)
10000
1000
100
10
1
0.1
0.01
1
10
100
1000
10000

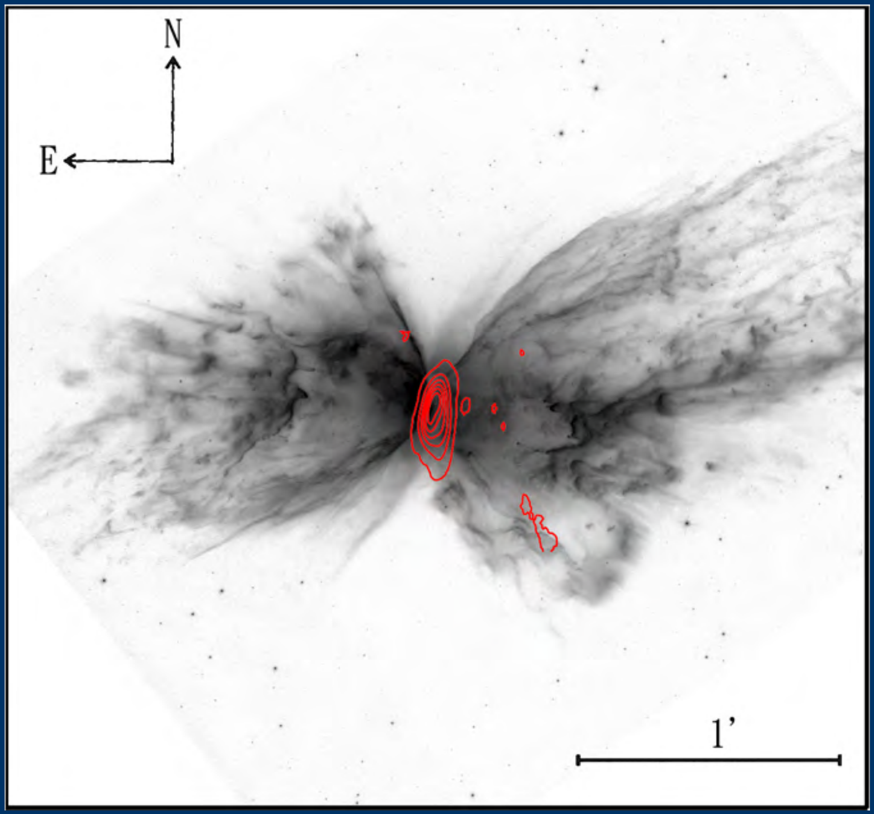
Ionized gas, dust, and molecular shells

- OH, CO, CO^+, CH, CH^+, HCN, HNC, HCO^+, H_2O, N_2H^+, CN, CS, C_2H, C_3H_2, SiS,
- 0.2 $M_\odot$ of ionized gas, 3 $M_\odot$ of molecular gas

CO outside of the ionized shell



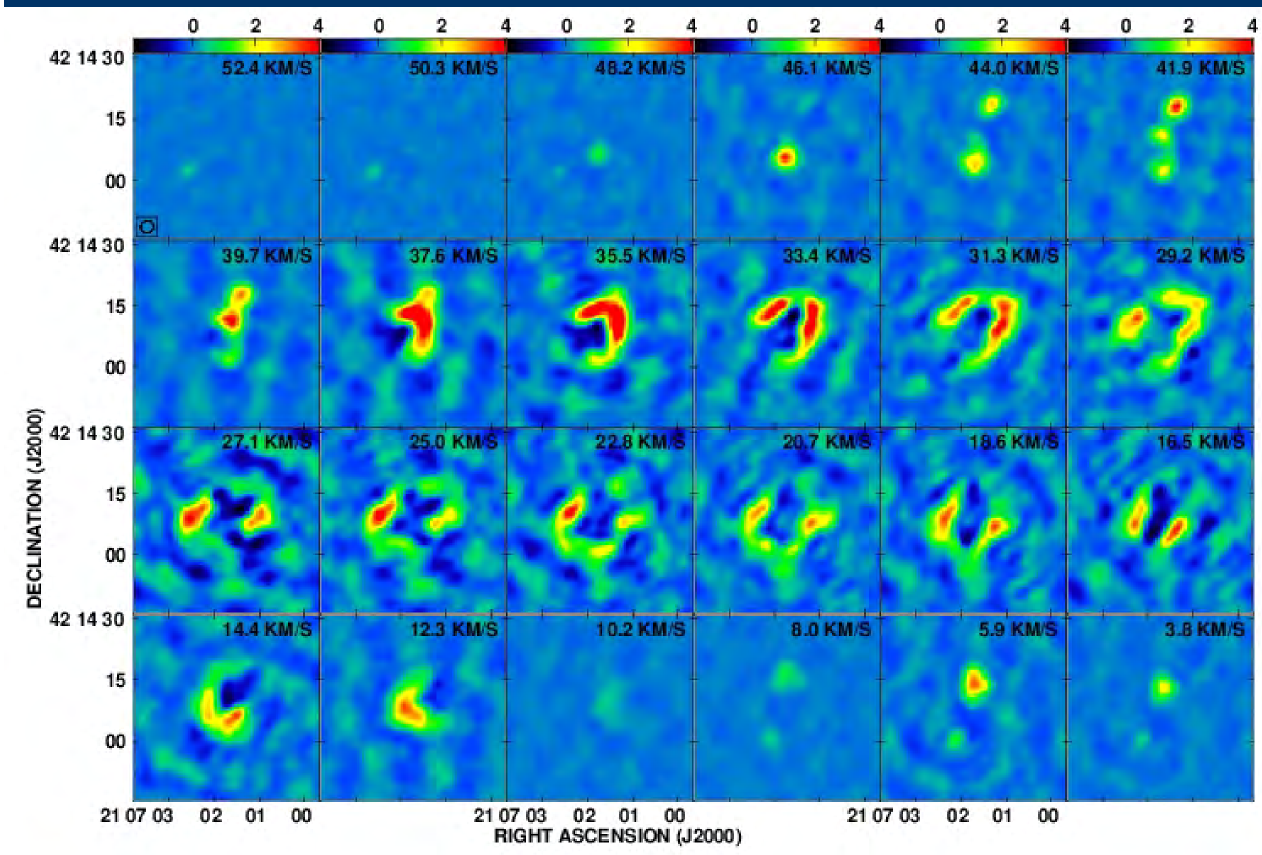
Relationship between the ionized gas, molecular, and dust components

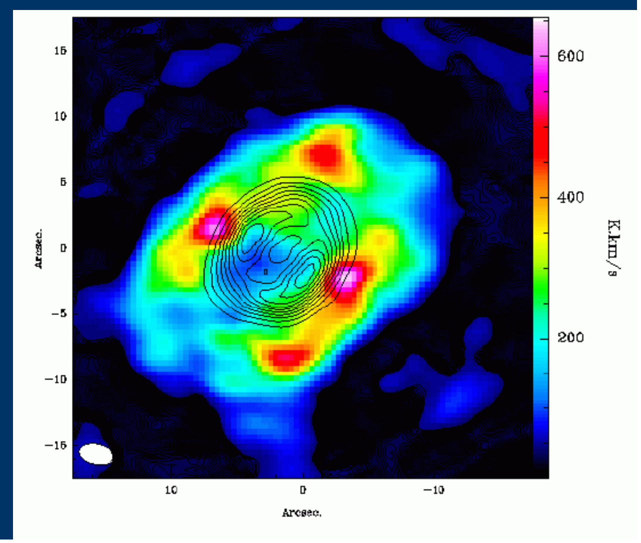


CO map from SMA

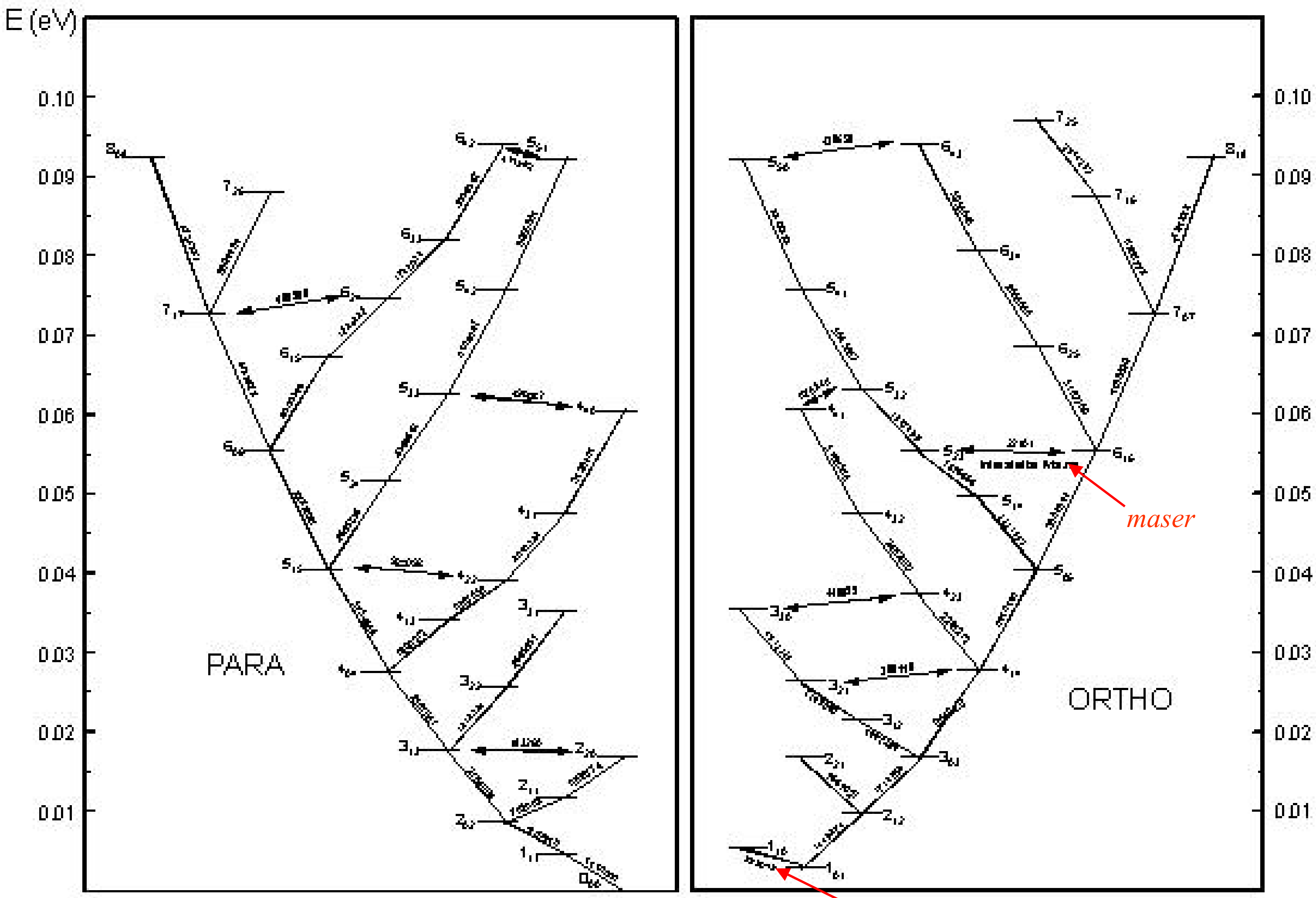
Optical bipolar lobes confined by external neutral matter

Line and continuum





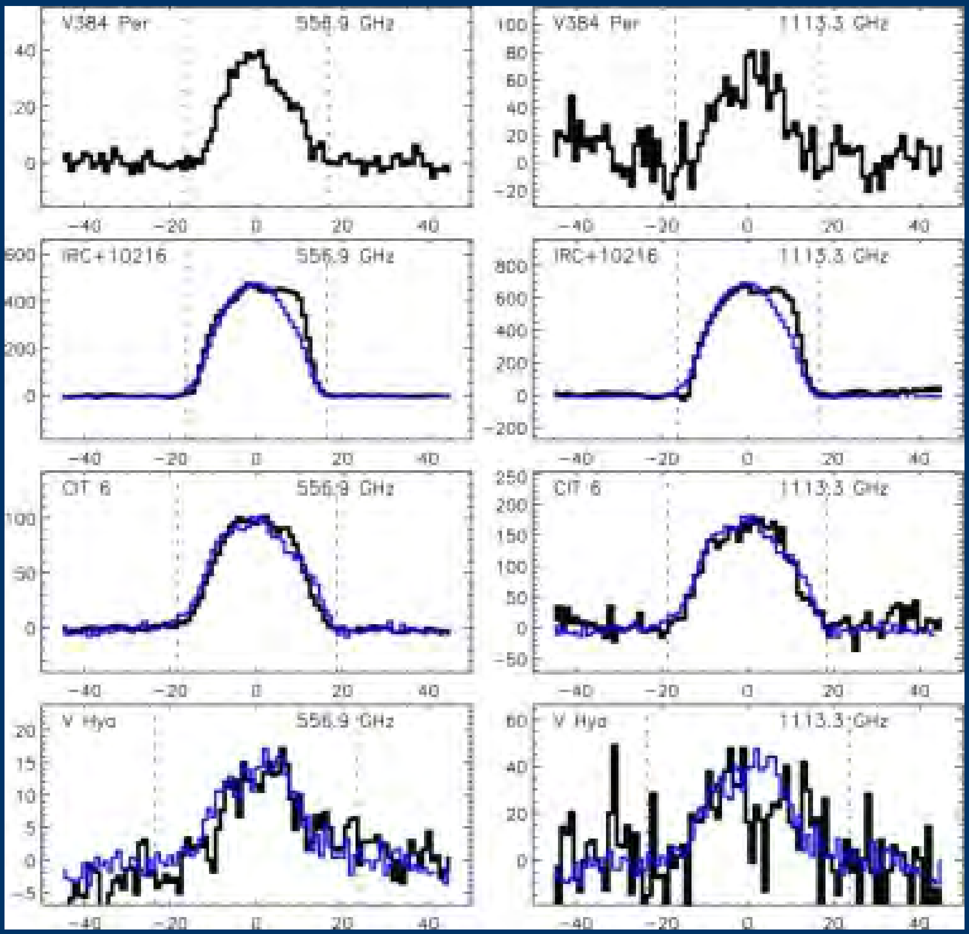
Water molecule



From Kuiper Belt?

557 GHz, first detected in IRC10216 by SWAS

Water in stars



Consistent profiles: not compatible to a flat disc (Kuiper Belt) model

Ortho 1_{10}-1_{01}
557 GHz

Para 1_{11}-0_{00}
1113 GHz

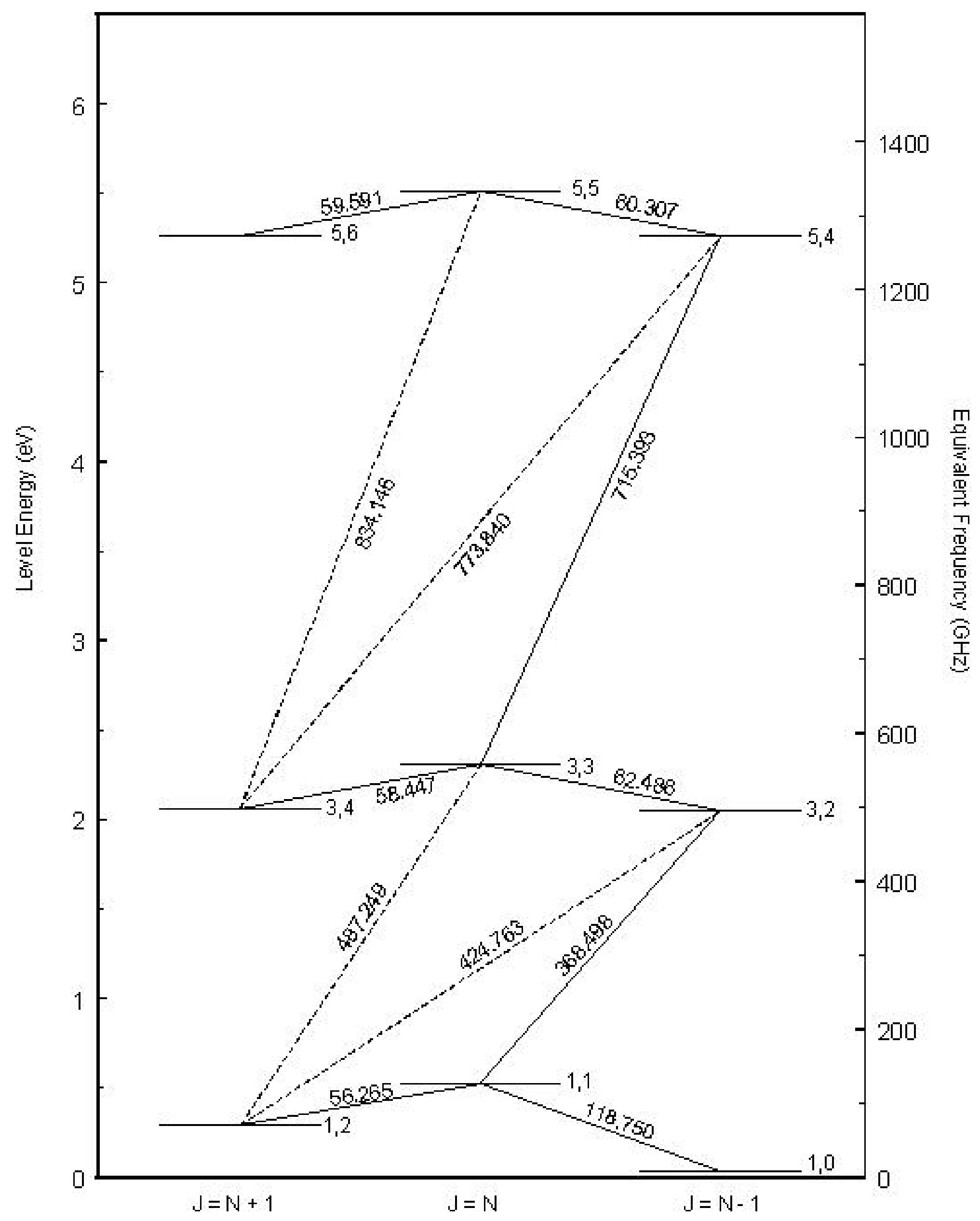
Fine structure lines

- Forbidden ($\Delta\ell=0$) fine structure transitions of atoms
- CI: $^3P_2$-$^3P_1$ (370 μm) and $^3P_1$-$^3P_0$ (609 μm)
- OI: $^3P_1$-$^3P_2$ (63 μm) and $^3P_0$-$^3P_1$ (145 μm)
- Common ions: $^2P_{3/2}$-$^2P_{1/2}$ line of C^+ at 158 μm
- $^3P_2$-$^3P_1$ (122 μm) and $^3P_1$-$^3P_0$ (205 μm) lines of N^+
- Hyperfine lines: $^2P_{3/2}$=$^2P_{1/2}$ F=2-1 $^{13}C^+$ line at 158 μm

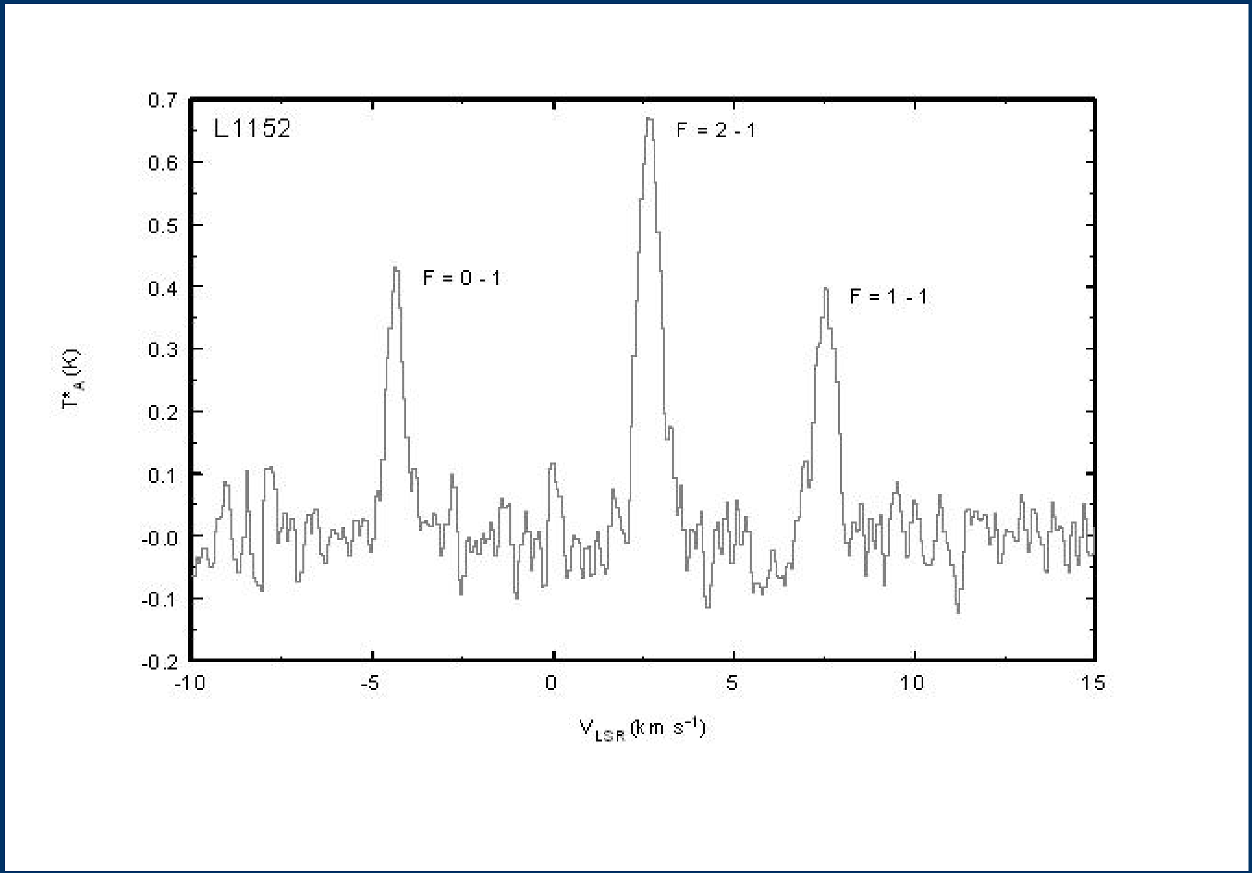
Molecular Oxygen

- O_2 is a boson ($I=0$)⇒symmetry with exchange of two nuclei
- Electronic state antisymmetric⇒only rotational states with odd J are allowed
- Ground state $^3\Sigma$ ($S=1$, $L=0$)
- Fine structure splitting $J=N$, $N\pm1$

- Magnetic dipole fine structure line ($\Delta J=\pm1$)
- *N=1, J=1→0* transition at 119 GHz
- Magnetic dipole rotational transitions $\Delta N=2$, $\Delta J=\pm1$
- $(N,J)=3,3\rightarrow1,2$ at 487 GHz, $(N,J)=3,2\rightarrow1,2$ at 425 GHz



Hyperfine lines of molecules



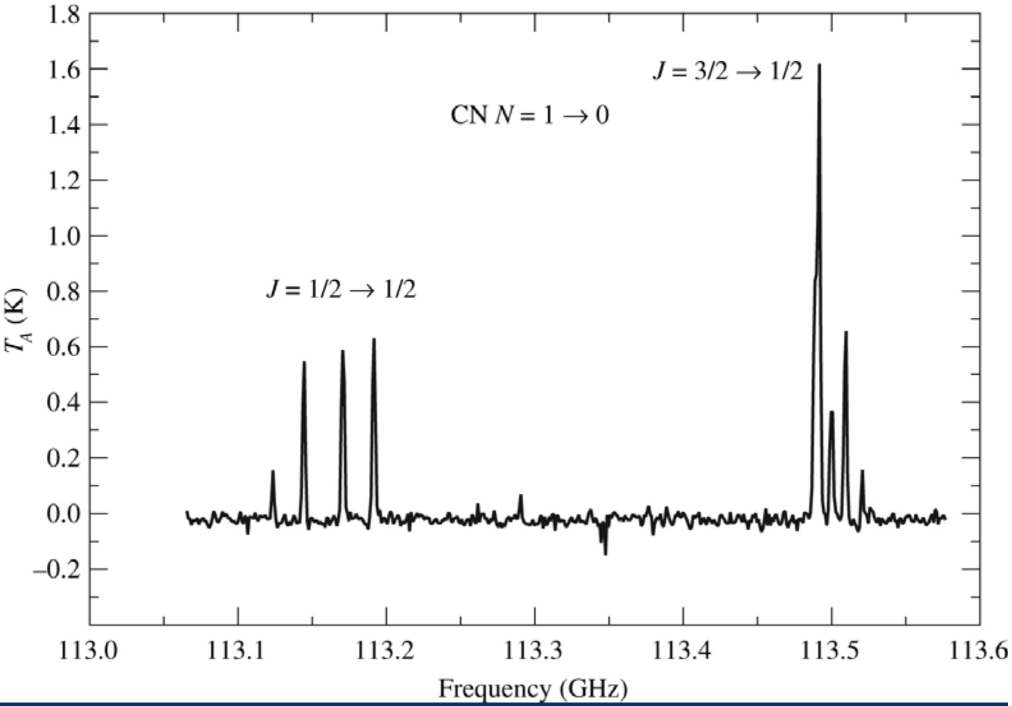
- F=J+I
- ^{14}N has I=1
- The J=1-0 line of HCN are split into F=0-1, F=2-1, F=1-1

Radicals

- Molecules that contain an unpaired electron but not charged (S=½)
- Highly reactive and unstable
- OH, CN, C_4H, C_6H, C_8H….
- Often detected in space before studied in lab

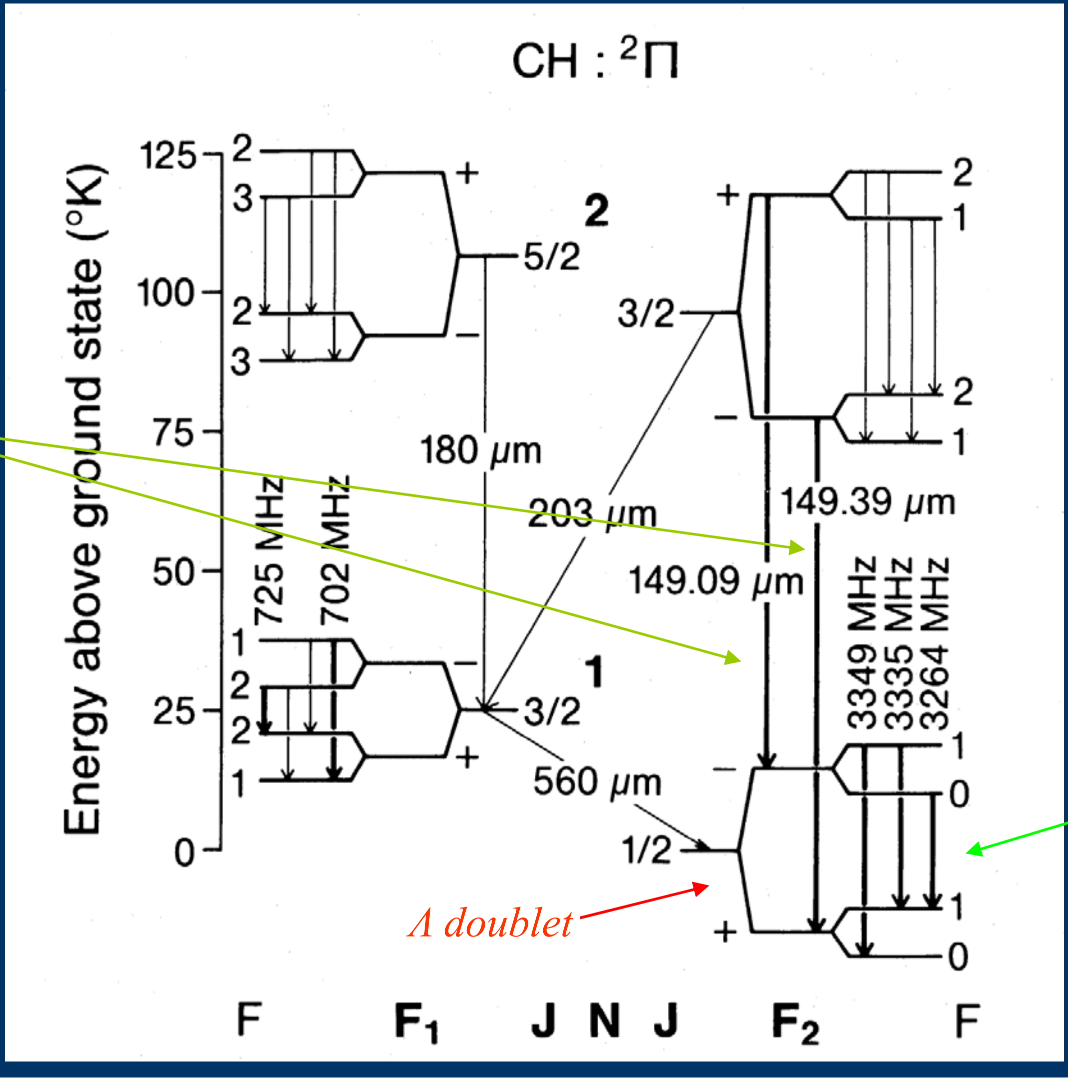
CN (cyanogen)

- Ground electronic state $X^2\Sigma^+$
- $J = N + L + S = N + 0 + ½ = N \pm ½$
- Since nuclear spin of N is 1, $F = J \pm 1$, there are 9 hyperfine transitions in the $N = 1 \rightarrow 0$ rotational transition



The CH radical

Rotational lines in THz range, first detected by KAO



Λ doublet

hyperfine

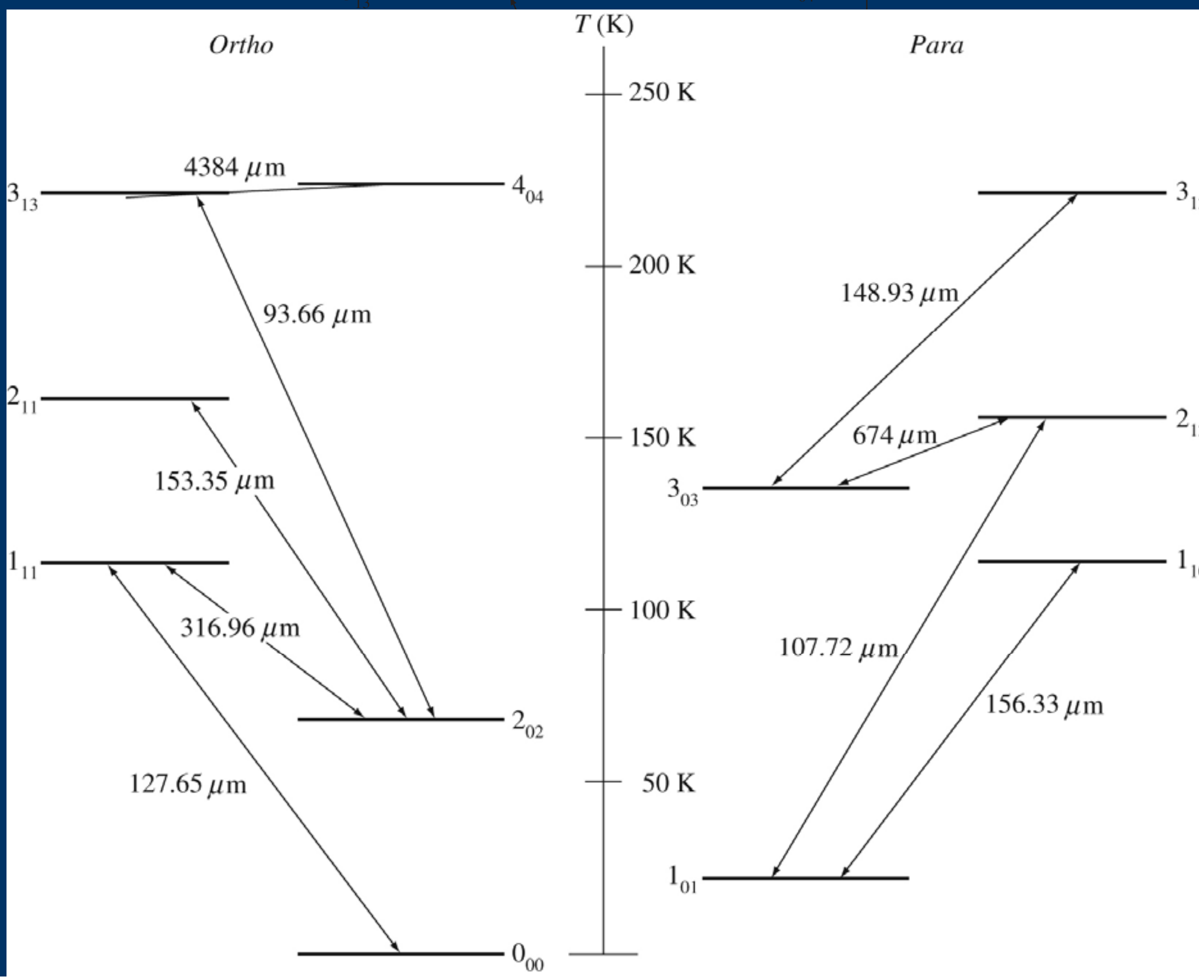
Two unpaired electrons

Methylene (CH_2)

- Simplest neutral polyatomic molecule with a triplet electronic ground state $^3B_1$ *(S=1)*
- Asymmetric top ($N_{K-1,\ K1}$)
- Fine structure states *J=N-1, N, N+1*
- Two H atoms each with *I=½*, CH_2 can be in ortho (*I=1*) or para (*I=0*) forms
- Ortho has hyperfine states: *F=J-1, J, J+1*

Low rotational levels of CH_2

ortho *para*



All lines in the far IR

Molecular Ions

J=2-1, 3-2, 4-3 at 180, 120, and 90 μm detected by ISO

- CH^+: rotational transitions in the submm because of light weight
- HCO^+ (X-ogen): the most abundant molecular ion
- Gas-phase, neutral-ion reactions are important in the production of neutral molecules under low temperatures

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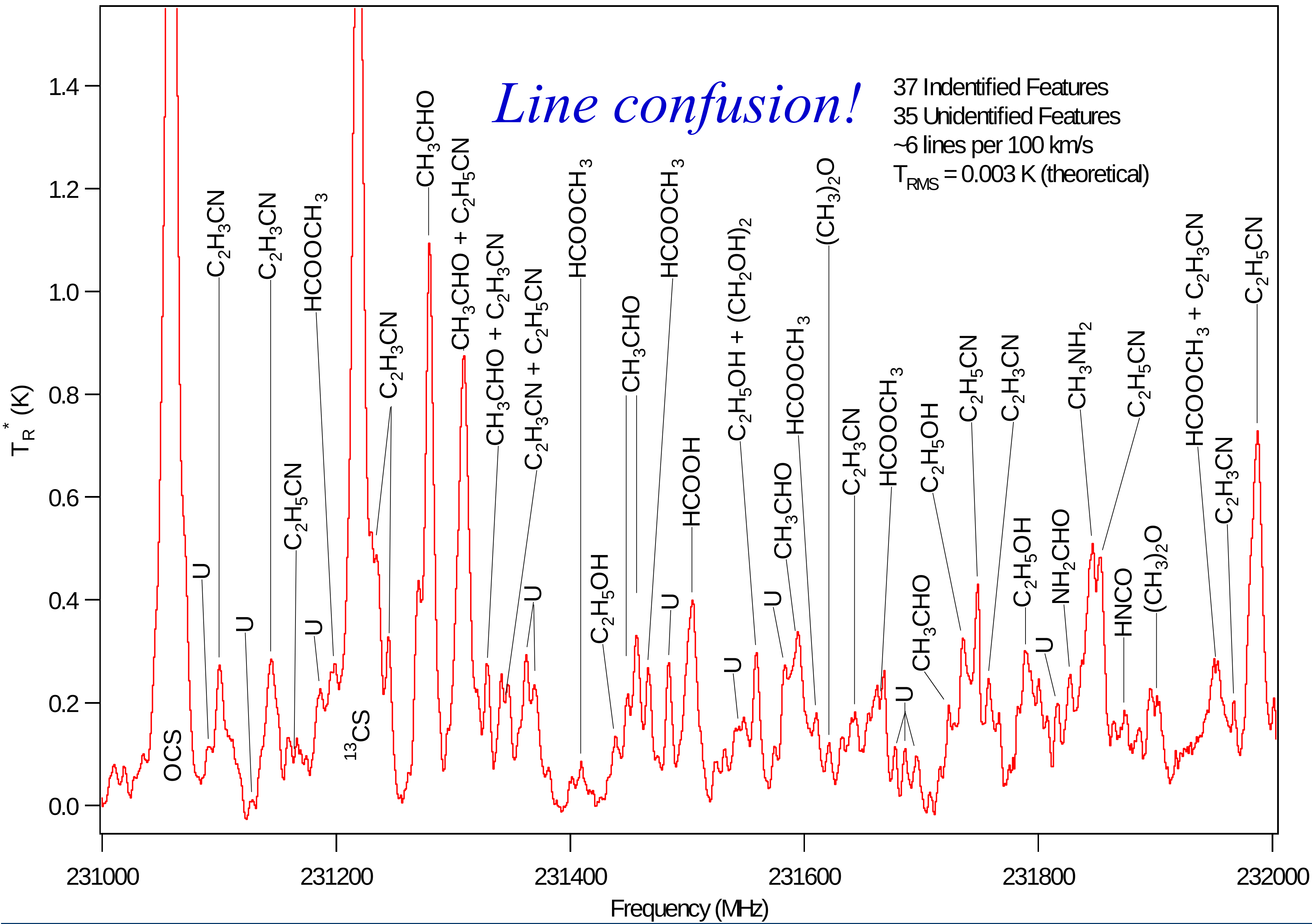

A line everywhere!

Summary

- Future cm, mm, and submm interferometers can study stars with increased sensitivity, angular resolution, and dynamic range
- Time domain and imaging (4D: x-y-λ-t)
- Stellar radio astronomy holds the key to the understanding of morphology shaping
- Chemical synthesis in the late stages of stellar evolution: from acetylene to complex organics

Summary

- Fine structure and hyperfine structures lines of atomic, ionic, and molecular lines are observable
- Radicals and molecular ions can be used to probe the physical and chemical structures of the stellar envelopes