Sternentstehung - Star Formation

Sommersemester 2009

Henrik Beuther

3.4 Today: Introduction & Overview

10.4 Karfreitag

17.4 Physical processes I

24.4 Physcial processes II

1.5 Tag der Arbeit

8.5 Collapse models I

15.5 Collapse models II

22.5 Accretion disks

29.5 *No lecture*

5.6 Jet theory (Christian Fendt)

12.6 Observations of outflows and jets

19.6 Protostellar evolution, stellar birthline, pre-main sequence evolution

26.6 High-mass star formation, clusters and the IMF

3.7 Extragalactic star formation (Eva Schinnerer)

10.7 Summary

More Information and the current lecture files: http://www.mpia.de/homes/beuther/lecture_ss09.html

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Topics today

- Molecules and depletion

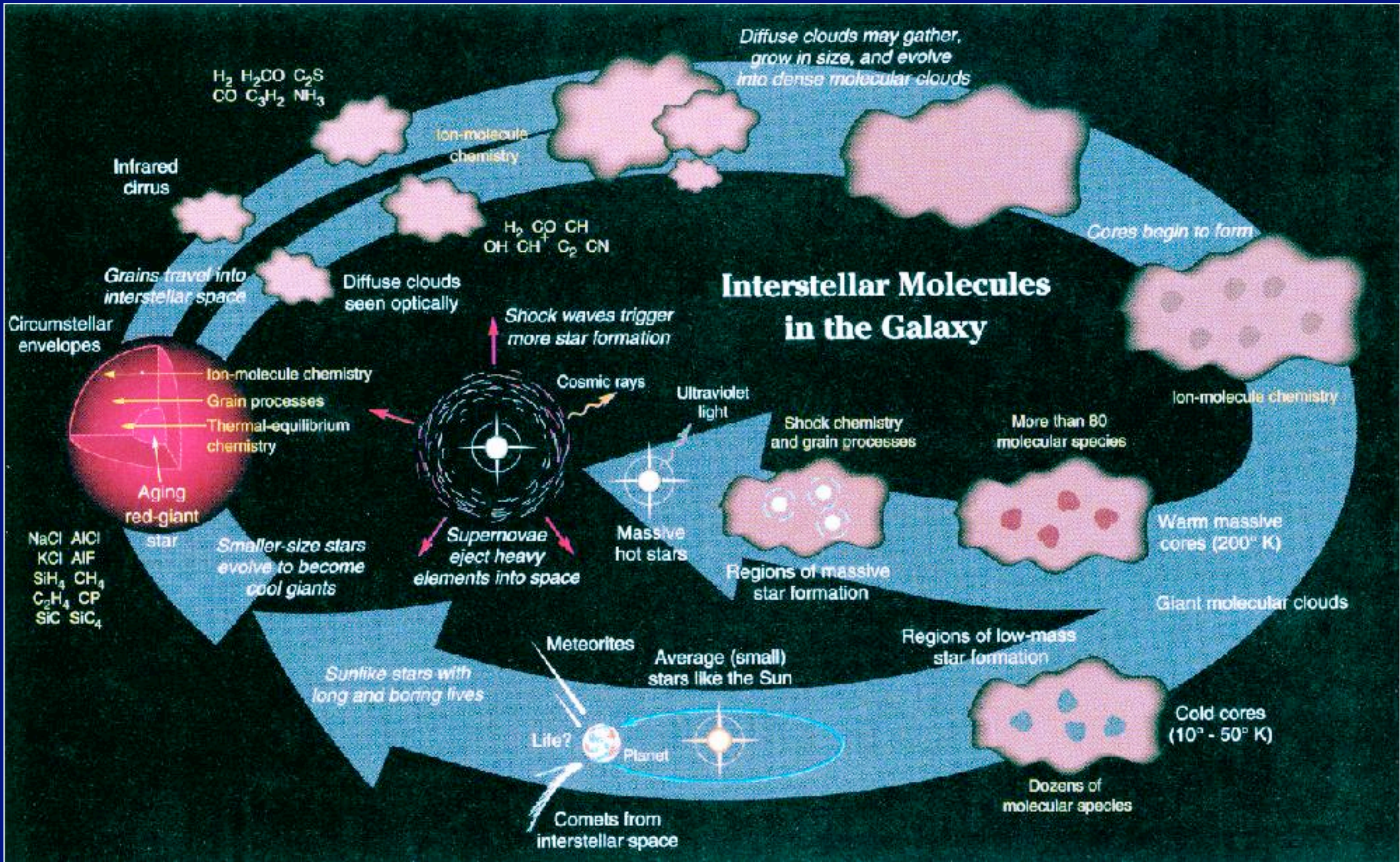
- Heating and cooling

- Radiation transfer and column density determination

- Line profiles

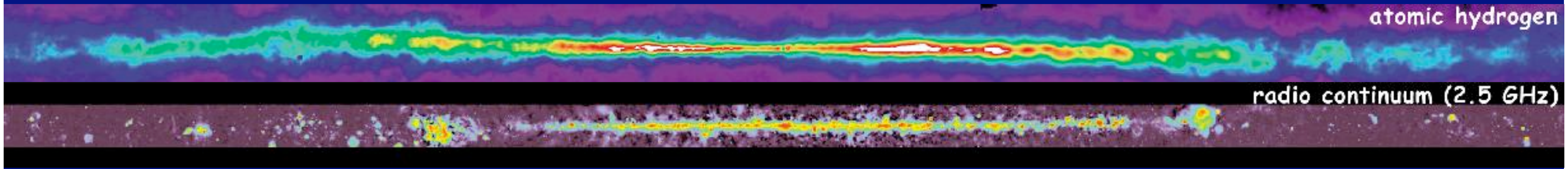
- Applications

The cosmic cycle

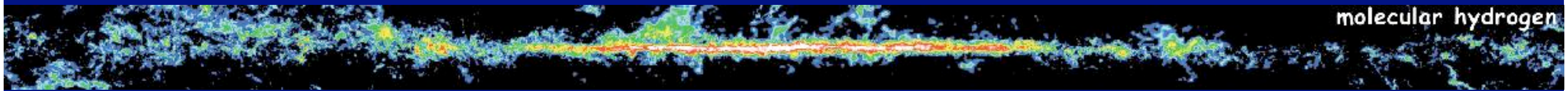


Basics I

Neutral and ionized medium



Stars form in the dense molecular gas and dust cores



<u>Most important astrophysical tools:</u>

Spectral lines emitted by various molecules

Absorption and thermal emission from dust

Basics II

High dust column densities block optical and UV-light in dark cores
--> important requirement that molecules can form and survive

History:

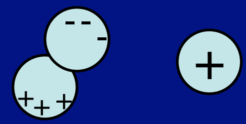
- Late 1930s: Detection of CH, CH^+ and CN in diffuse clouds by ab-sorption of optical light by background stars
- 1960s: Detection of OH, NH_3 and H_2O at radio wavelength

Formation of molecules is an energy problem, two atoms approach each other with positive total energy, hence would simply rebound if no energy could be given away someway … Possibilities:

- Simultaneous collision with 3rd atom carrying away energy
  --> unlikely at the given low densities
- Form a molecule in excited state, and then radiating away energy
  --> probablility of such radiative association low as well
- Neutral-neutral reactions from unstable "activated complexes" (intermediate between reactants and products) which may form larger molecules
  --> activation barrier ~100K, impossible on cold dark cores
- Ion-molecule or ion-atom reactions can solve energy problem
- Neutral-neutral reactions on dust grain surfaces (catalytic) important

Basics III

Ion induces dipole moment in atom or molecule which creates an electrostatic attraction between the two.
--> effective cross section increases over geometric values



Even at low temperatures such reactions can account for large fraction of interstellar molecules. However, there are not enough ions available at any time to account for large H_2 abundances
--> grain surface chemistry important

Simple molecules like CO or CS explainable by ion-molecule chemistry, less clear for complex molecules, grain surface chemistry important

No larger inorganic species than, e.g., NH_3, however large organic molecules --> carbon bond important in interstellar chemistry

CO most abundant molecule after H_2
--> most information about molecular clouds from CO observations

Molecules in Space

2	3	4	5	6	7	8	9	10	11	12	13 atoms
H2	C3	c-C3H	C5	C5H	C6H	CH3C3N	CH3C4H	CH3C5N?	HC9N	CH3OC2H5	HC11N
AlF	C2H	l-C3H	C4H	l-H2C4	CH2CHCN	HCOOCH3	CH3CH2CN	(CH3)2CO			
AlCl	C2O	C3N	C4Si	C2H4	CH3C2H	CH3COOH?	(CH3)2O	NH2CH2COOH?			
C2	C2S	C3O	l-C3H2	CH3CN	HC5N	C7H	CH3CH2OH	CH3CH2CHO			
CH	CH2	C3S	c-C3H2	CH3NC	HCOCH3	H2C6	HC7N				
CH+	HCN	C2H2	CH2CN	CH3OH	NH2CH3	CH2OHCHO	C8H				
CN	HCO	CH2D+?	CH4	CH3SH	c-C2H4O	CH2CHCHO					
CO	HCO+	HCCN	HC3N	HC3NH+	CH2CHOH						
CO+	HCS+	HCNH+	HC2NC	HC2CHO							
CP	HOC+	HNCO	HCOOH	NH2CHO							
CSi	H2O	HNCS	H2CHN	C5N							
HCl	H2S	HOCO+	H2C2O	HC4N							
KCl	HNC	H2CO	H2NCN								
NH	HNO	H2CN	HNC3								
NO	MgCN	H2CS	SiH4								
NS	MgNC	H3O+	H2COH+								
NaCl	N2H+	NH3									
OH	N2O	SiC3									
PN	NaCN	C4									
SO	OCS										
SO+	SO2										
SiN	c-SiC2										
SiO	CO2										
SiS	NH2										
CS	H3+										
HF	SiCN										
SH	AlNC										
FeO(?)	SiNC										

About 150 detected interstellar molecules as of April 2009 (www.cdms.de).
36 (+2 tentative) molecular detection in extragalactic systems.

A few important molecules

Mol.	Trans.	Abund.	Crit. Dens. [cm^{-3}]	Comments
H_2	1-0 S(1)	1	$8x10^7$	Shock tracer
CO	J=1-0	$8x10^{-5}$	$3x10^3$	Low-density probe
OH	$^2\Pi_{3/2}$;J=3/2	$3x10^{-7}$	$1x10^0$	Magnetic field probe (Zeeman)
NH_3	J,K=1,1	$2x10^{-8}$	$2x10^4$	Temperature probe
CS	J=2-1	$1x10^{-8}$	$4x10^5$	High-density probe
SiO	J=2-1		$6x10^5$	Outflow shock tracer
H_2O	6_{16}-5_{23}		$1x10^3$	Maser
H_2O	1_{10}-1_{11}	$<7x10^{-8}$	$2x10^7$	Warm gas probe
CH_3OH	7-6	$1x10^{-7}$	$1x10^5$	Dense gas/temperature probe
CH_3CN	19-18	$2x10^{-8}$	$2x10^7$	Temperature probe in Hot Cores

Basics IV

<u>Depletion of molecules on dust grains</u>

The grains are moving at v_{therm} relative to molecules

$E = 1/2\ mv^2_{therm} = 3/2\ k_bT \quad \Rightarrow v_{therm} = (3k_bT/m)^{1/2}$

n grains sweeps out cylindrical volume in time Δt of

$n(\pi a^2)v_{therm}\Delta t$ (a: grain radius)

Probability of molecule in volume V to be struck by grain in time Δt

$P(\Delta t)/V = n(\pi a^2)v_{therm}\Delta t\ /V$

Hence the collision time t_{coll}

$t_{coll} = 1/(n(\pi a^2)v_{therm}) = 1/(n_H\Sigma v_{therm})$ (n_H: density; Σ: cross section)

For example CS: $v_{therm} \sim 5x10^3$cm s^{-1} at 10K, and $n_H \sim 10^4$cm^{-3}

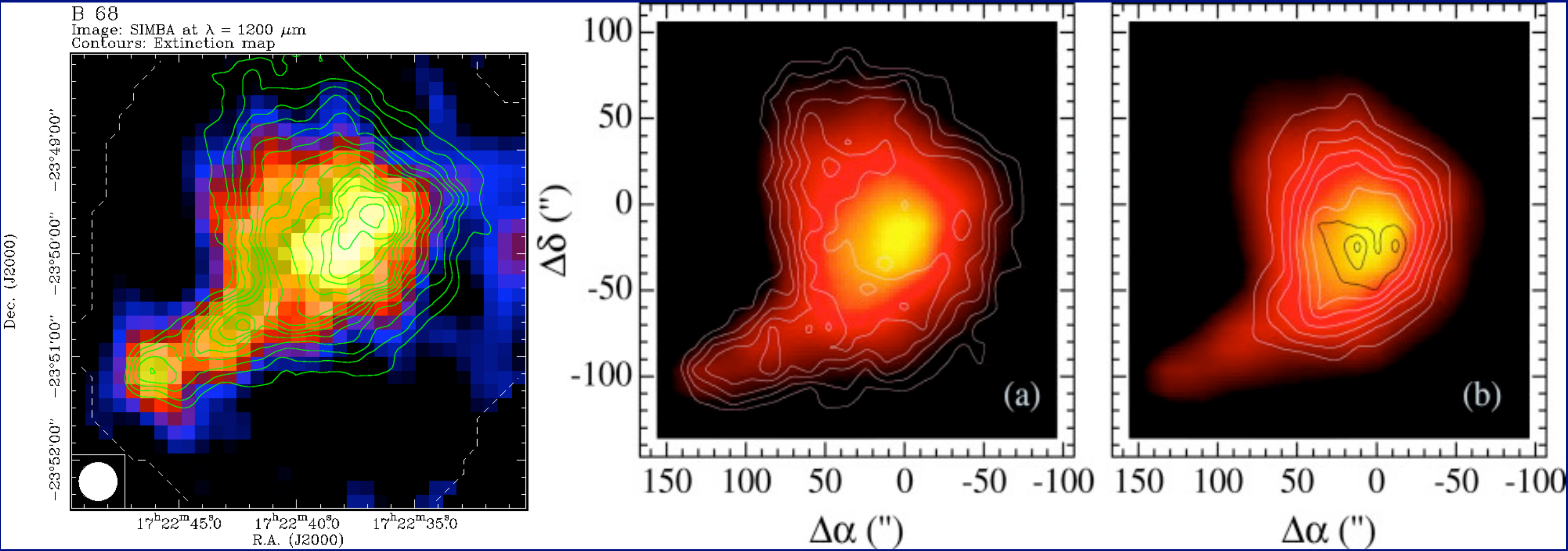
$t_{coll} \sim 6x10^5$ yr

Depletion time-scale very short

--> mechanisms for reinjecting molecules from grains important

Depletion example

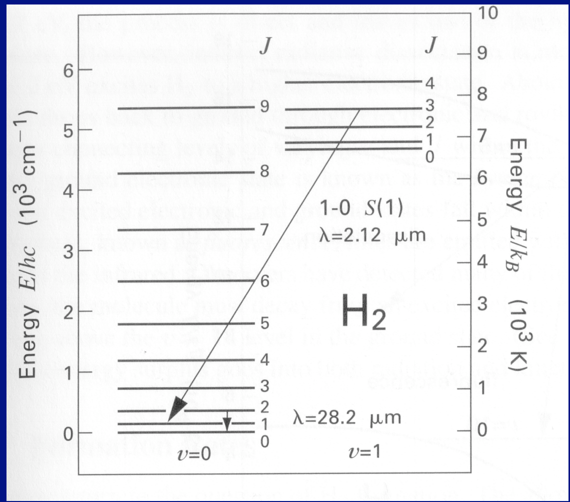
1.2 mm Dust Continuum $C^{18}O$ N_2H^+



Possible mechanisms working against depletion:
- UV radiation (not working in dense cores)
- In small grain, heat from chemical grain surface reactions could raise temperature
- Kelvin-Helmholtz contraction and energy
- Ignited central protostar
- Shocks
- …

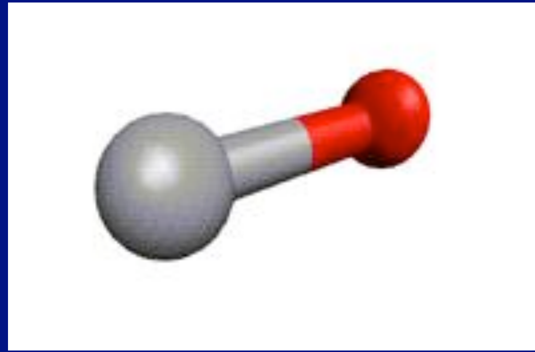
Molecular Hydrogen (H_2)

- Since H_2 consists of 2 identical atoms, it has no electric dipol moment and rotationally excited H_2 has to radiate via energetically higher quadrupole transitions with excitation temperatures > 500 K.
  --> cold clouds have to be observed other ways, e.g., CO

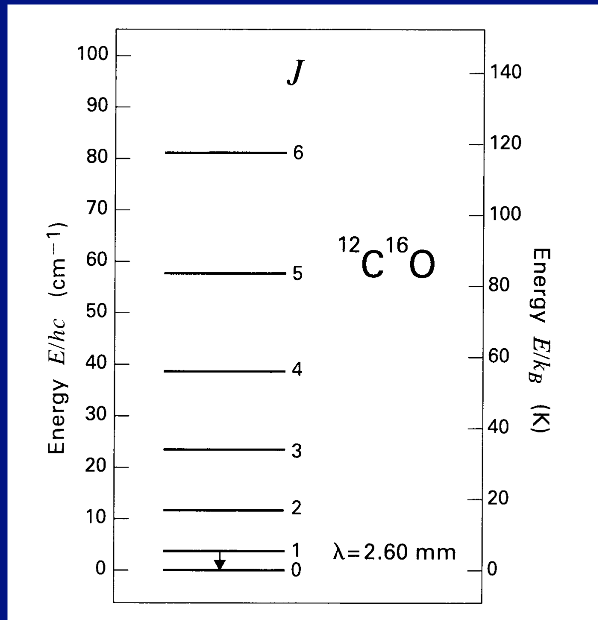


- H_2 can be detected in hot environment.
  Rotational energy:
  Classical mechanics: $E_{rot} = J^2/2I$
  (J: Angular momentum; I: Moment of inertia)
  Quantum-mechanical counterpart: $E_{rot} = h^2/2I \times J(J+1)$
  $= BhI \times J(J+1)$
  (J: rotational quantum number; B: rotational constant)
- Small moment of inertia --> large spread of energy levels
  Allowed quadrupole transitions $\Delta J = 2$
  --> lowest rotational transition J=2-0 has energy change of 510 K

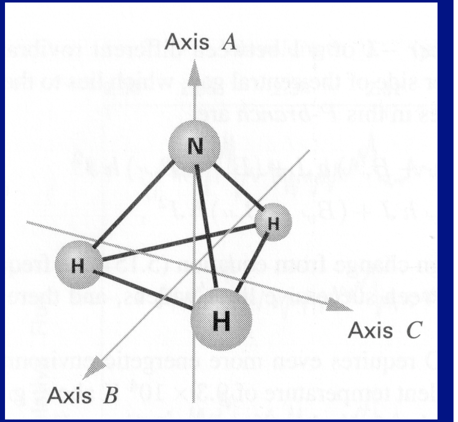
Carbon monxide (CO)



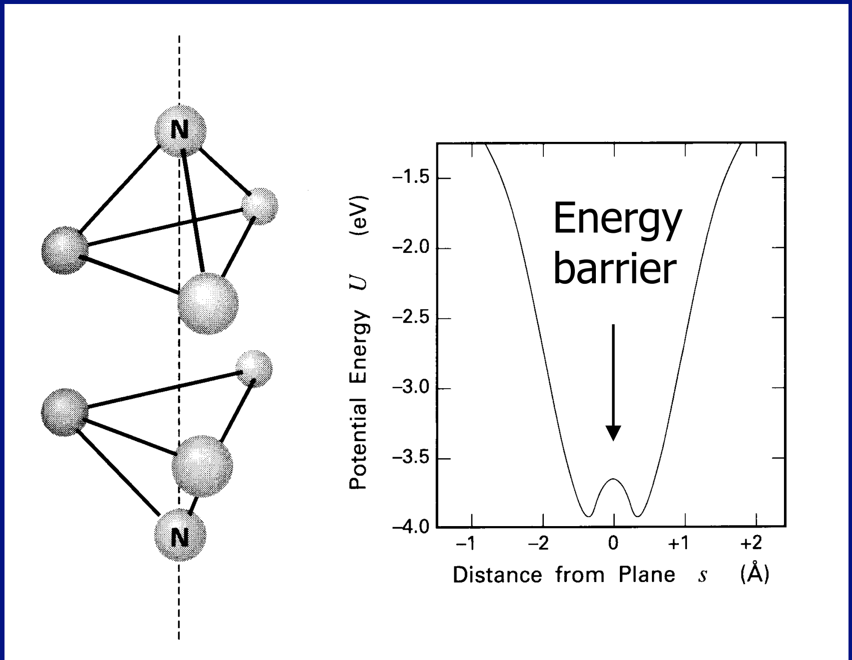
- Forms through gas phase reactions.
- Strong binding energy of 11.1 eV helps to prevent much further destruction (self-shielding).
- Has permanent dipole moment --> strong emission at (sub)mm wavelengths.
- Larger moment of inertia than H_2.
  --> more closely spaced rotational ladder, J=1 level at 4.8×10^{-4}eV or 5.5K above ground
- In molecular clouds excitation mainly via collisions with H_2.
- Critical density for thermodynamic equilibrium with H_2 $n_{crit} = A/\gamma \sim 3\times10^3 cm^{-3}$.
  (A: Einstein A coefficient; γ: collision rate with H_2)
- The level population follows a Boltzmann-law:
  $n_{J+1}/n_J = g_{J+1}/g_J \exp(-\Delta E/k_B T_{ex})$ (for CO, the statistical weights $g_J = 2J + 1$)
  The excitation temperature T_{ex} is a measure for the level populations and equals the kinetic temperature T_{kin} if the densities are > n_{crit}.

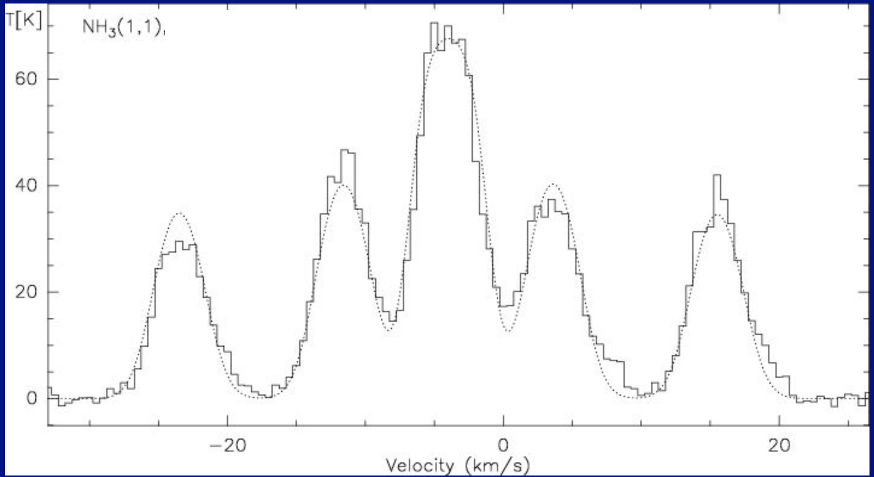


Ammonia (NH_3)



- Formed through gas-phase reactions.
- Symmetric-top molecule
- $E_{rot} = J^2_A/2I_A + J^2_B/2I_B + J^2_C/2I_C$
  --> However, useful transitions only at very high freq.
- Most useful transitions are the inversion transitions around 25GHz.
  --> tunneling energy barrier
- Additional effects (non-spherical charge distribution, quadr. mom., magn. interaction between spins) causes further hyperfine splitting.





Topics today

- Molecules and depletion
- Heating and cooling
- Radiation transfer and column density determination
- Line profiles
- Applications

Heating processes

UV radiation from stars
Energy injection from supernovae
Energy injection from outflows/jets
Cosmic rays interaction with HI and H_2
(consist mainly of relativistic protons accelerated within magnetized shocks produced by supernova-remnant--molecular cloud interactions)
$p^+ + H_2 \text{-->} H_2^+ + e^- + p^+$ (dissociation: ions also important for ion-molecule chemistry)
Interstellar radiation (diffuse field permeating interstellar space)
Mainly dissociates carbon (lower ionization potential than H_2)
$C + h\nu \text{-->} C^+ + e^-$ The electron then disperses energy to surrounding atoms by collisions.
Photoelectric heating: - Heats grains which re-radiate in infrared regime
- UV photons eject e^- from dust and these e^- heat surrounding gas via collisions

Cooling processes

Major constituents H & H_2 have no dipole moment and hence cannot effectively cool in quiescent molecular cloud. Other coolants required.

--> Hydrogen collides with ambient atoms/molecules/grains exciting them. The cooling is then done by these secondary constituents.

$O + H \rightarrow O + H + h\nu$ collisional excitation (FIR)

$C^+ + H \rightarrow C^+ + H + h\nu$ fine structure excitation (FIR)

$CO + H_2 \rightarrow CO + H_2 + h\nu$ rotational excitation (radio/(sub)mm)

At higher densities other molecules come into play, e.g., H_2O.

The low-J CO lines are mostly optically thick, the energy diffuses from region to region and escapes from cloud surface. Higher J lines cool directly. CO is the most effective coolant in molecular clouds.

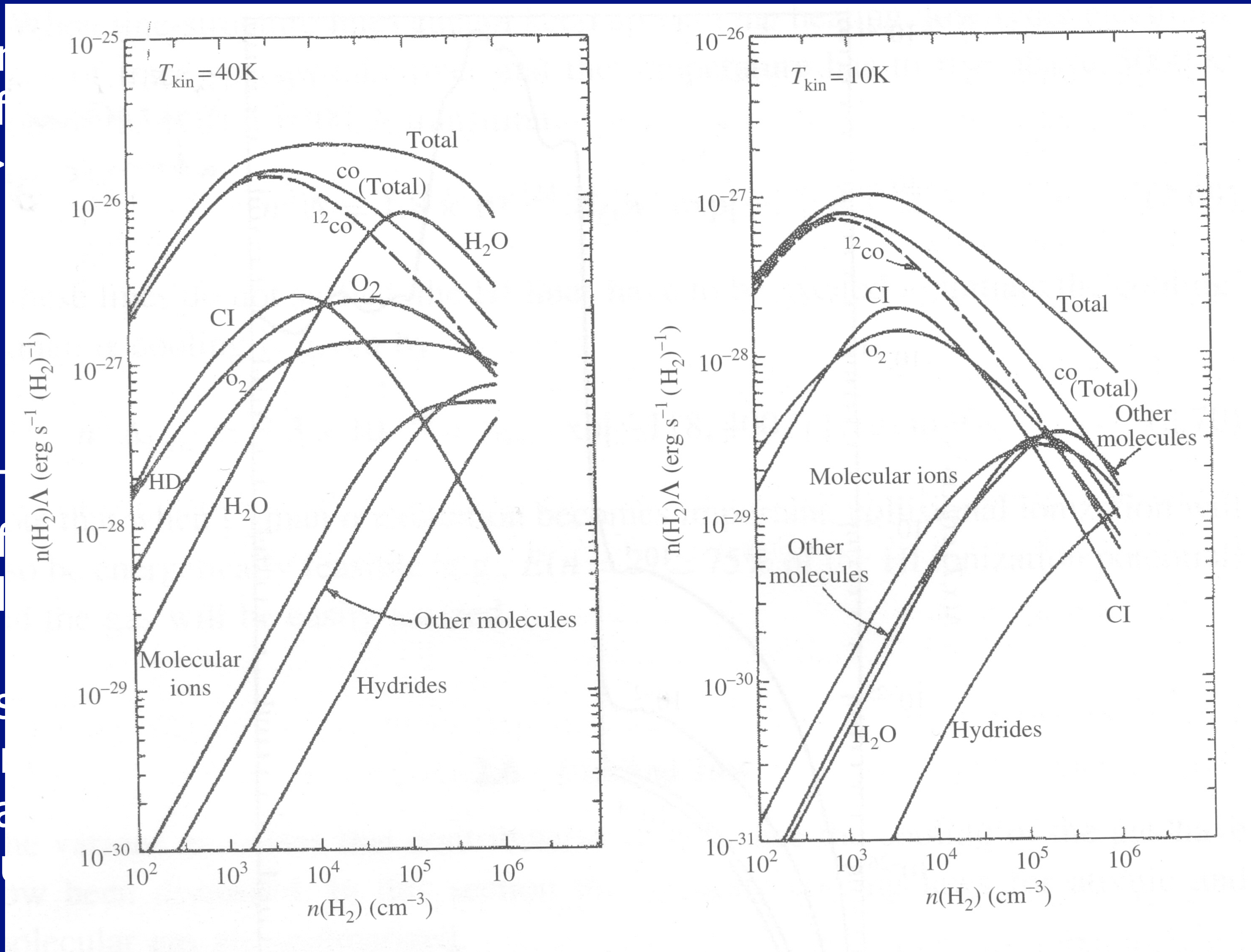
Collisions with gas atoms/molecules cause lattice vibrations on grain surfaces, that decay through the emission of infrared photons (since grains are also heated by radiation gas and dust temperature are usually not equal).

Cooling processes

Major … t
eff … ired.
--> … ng
… nts.

… mm)
… , H_2O.
T … es
f …
I … clouds.

Collis … n
su … nce
gra …
us …



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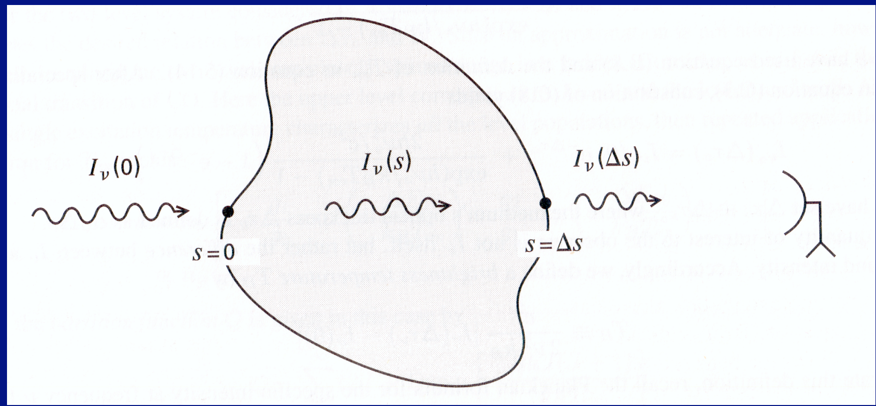
Radiation transfer I



$$dI_\nu = -\kappa_\nu I_\nu ds + \varepsilon_\nu ds$$

with the opacity

$$d\tau_\nu = -\kappa_\nu ds$$

and the source function

$$S_\nu = \varepsilon_\nu/\kappa_\nu$$

$$\Rightarrow dI_\nu/\,d\tau_\nu = I_\nu - S_\nu$$

Assuming a spatially constant source function → radiation transfer equation

$$\Rightarrow I_\nu = S_\nu\,(1 - e^{-\tau\nu}) + I_{\nu,0}e^{-\tau\nu}$$

Radiation transfer II

The excitation temperature T_{ex} is defined via a Boltzmann distribution as

$$n_J/n_{J-1} = g_J/g_{J-1} \exp(-h\nu/kT_{ex})$$

with n_J and g_J the number density and statistical weights.

In case of rotational transitions

$$g_J = 2J + 1$$

In thermal equilibrium

$$T_{ex} = T_{kin}$$

In a uniform molecular cloud the source function S_ν equals Planck function

$$S_\nu = B_\nu\,(T_{ex}) = 2h\nu^3/c^2\,(\exp(h\nu/kT_{ex}) - 1)^{-1}$$

And the radiation transfer equation

$$\Rightarrow I_\nu = B_\nu\,(T_{ex})\,(1 - e^{-\tau\nu}) + I_{\nu,0}e^{-\tau\nu}$$

In the Rayleigh-Jeans limits ($h\nu << kT$) B equals

$$B = 2k\nu^2/c^2\,T \quad (\text{def.} \rightarrow T = c^2/(2k\nu^2)\,I_\nu)$$

And the radiation transfer equation using now the radiation temperature is

$$T_r = J_\nu\,(T_{ex})\,(1 - e^{-\tau\nu}) + J_{\nu,0}\,(T_{bg})e^{-\tau\nu}$$

With

$$J_\nu = h\nu/k\,(\exp(h\nu/kT) - 1)^{-1}$$

Subtracting further the background radiation

$$T_r = (J_\nu(T_{ex}) - J_{\nu,0}(T_{bg}))\,(1 - e^{-\tau\nu})$$

Molecular column densities

To derive molecular column densities, 3 quantities are important:

1) Intensity T of the line
2) Optical depth τ of the line (observe isotopologues or hyperfine structure)
3) Partition function Q

The optical depth τ of a molecular transition can be expressed like

$$\tau = c^2/8\pi\nu^2 \; A_{ul}N_u \; (\exp(h\nu/kT) -1) \; \phi$$

With the Einstein A_{ul} coefficient

$$A_{ul} = 64\pi^4\nu^3/(3c^3h) \; \mu^2 \; J_u/(2J_u-1)$$

And the line form function ϕ

$$\phi = c/\nu \; 2\mathrm{sqrt}(\ln 2)/(\mathrm{sqrt}(\pi)\Delta\nu)$$

Using furthermore the radiation transfer eq. ignoring the background

$$T = J_\nu\,(T_{ex}) \; \tau\,(1 - e^{-\tau})/\tau$$

And solving this for N_u, one gets

$$N_u = 3k/8\pi^3\nu \; 1/\mu^2 \; (2J_u-1)/J_u \; \tau\,/(1 - e^{-\tau}) \; (T\Delta\nu \; \mathrm{sqrt}(\pi)/(2\mathrm{sqrt}(\ln 2))$$

The last expression equals the integral $\int$ T dv.

The column density in the upper level N_u relates to the total column density N_{tot}

$$N_{tot} = N_u/g_u \; Q \; \exp(E_u/kT)$$

For a linear molecule like CO, the partition function can be approximated to

$$Q = kT/hB.$$

However, for more complex molecules Q can become very complicated.

Conversion from CO to H_2 column densities

One classical way to derive conversion factors from CO to H_2 column densities and gas masses essentially relies on three steps:

1) Derive ratio between colour excess E_{B-V} and optical extinction A_v

$$A_v = 3.1\,E_{B-V} \quad \text{(Savage and Mathis, 1979)}$$

2) The ratio $N(H_2)/E_{B-V}$: One can measure the H_2 column density, e.g., directly from UV Absorption lines.

3) The ratio $N(CO)/A_v$: In regions of molecular gas emission, one can estimate A_v by star counts in the Infrared regime

⇒ Combining these three ratios, the CO observations can directly be converted to H_2 column densities. Assumptions about the 3D cloud geometry allow further estimates about the cloud masses and average densities.

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Line broadening

Natural line broadening: Disturbance of molecule by zero-point vibrations of electromagnetic field (or from thermal electromagnetic field)

$d\nu = 32\pi^3\nu^3 \mu^2/(3hc^3)$ (μ: Dipole moment)

For CO(1-0) at 20K → $d\nu \sim 3.5\text{x}10^{-8}$ or $dv \sim 9\text{x}10^{-14}$ km/s

→ Negligable!

Pressure broadening: Arises from collisions between molecules. Complex quantum-mechanical problem for intermolecular forces. At densities of star-forming regions negligable.

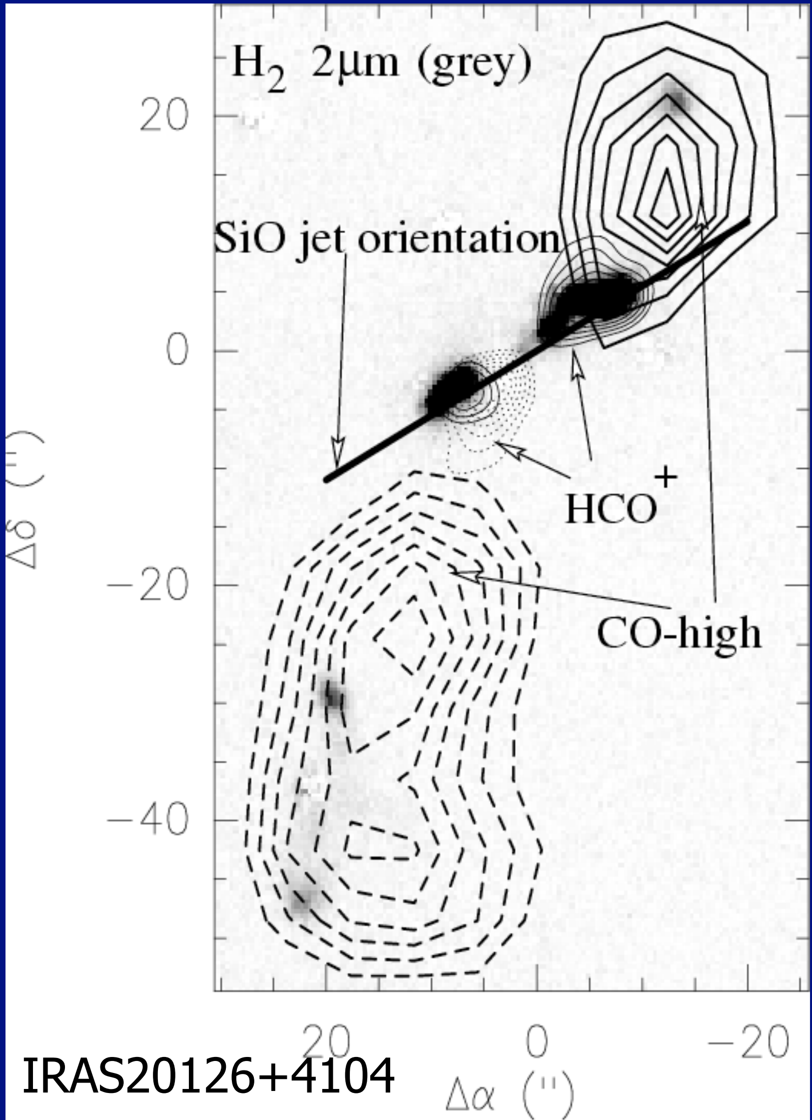
Thermal line broadening: Thermal motions of gas cause doppler broadening:

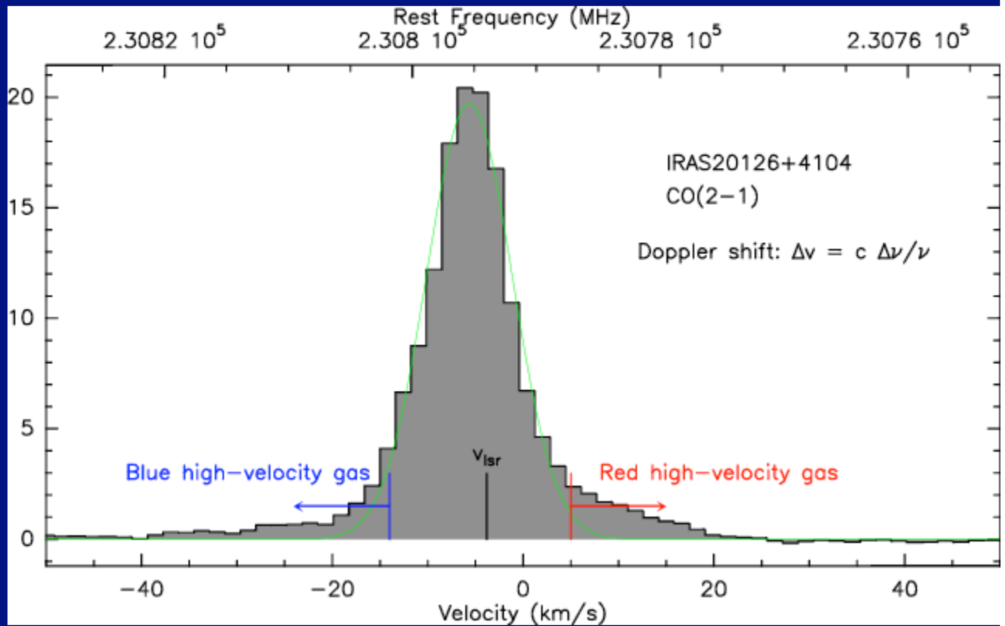
$dv = \text{sqrt}(8\ln 2\ kT/m_{mol})$

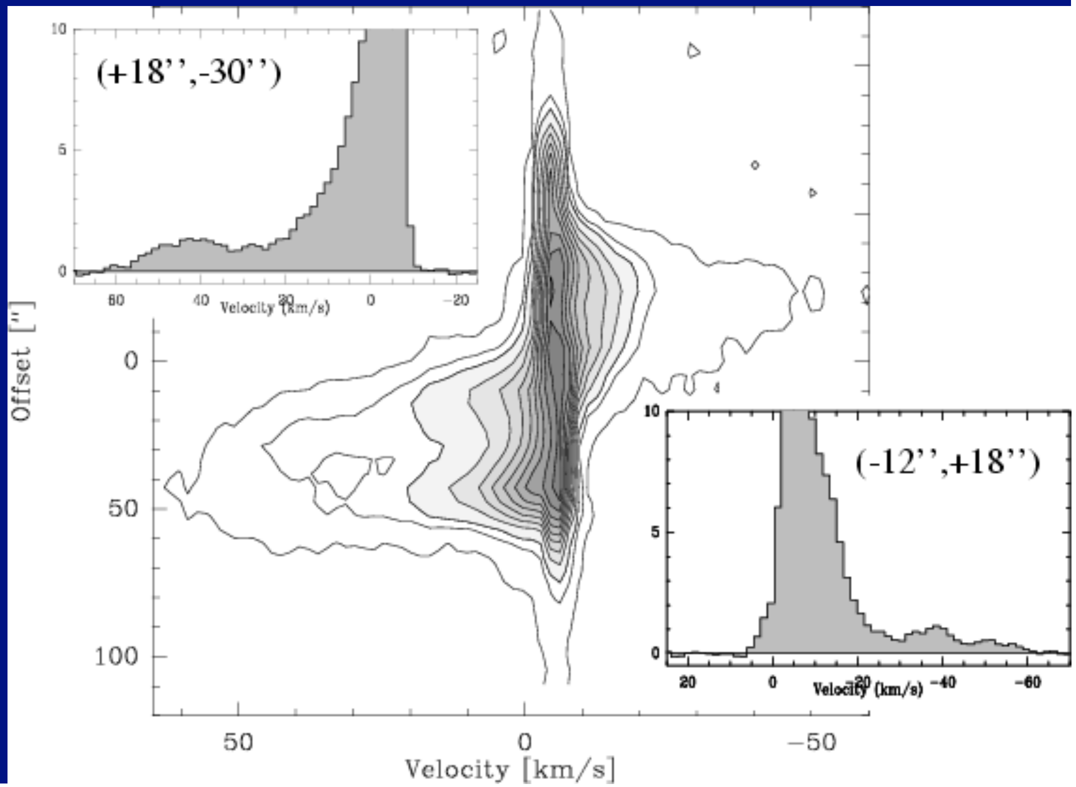
$dv(NH_3@30K) \sim 0.28$ km/s

Other physical effects: Line broadening due to outflow motions, rotation …

Molecular outflows







Lebron et al. 2006

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Applications I: Molecular gas structure of the Galaxy based on CO observations

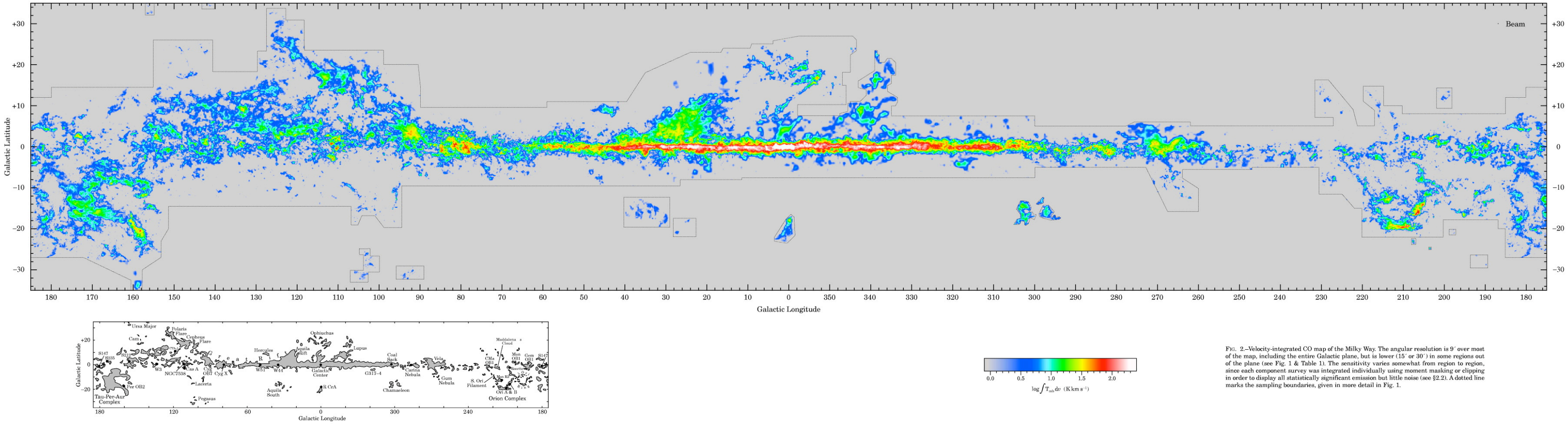


FIG. 2.–Velocity-integrated CO map of the Milky Way. The angular resolution is 9′ over most of the map, including the entire Galactic plane, but is lower (15′ or 30′) in some regions out of the plane (see Fig. 1 & Table 1). The sensitivity varies somewhat from region to region, since each component survey was integrated individually using moment masking or clipping in order to display all statistically significant emission but little noise (see §2.2). A dotted line marks the sampling boundaries, given in more detail in Fig. 1.

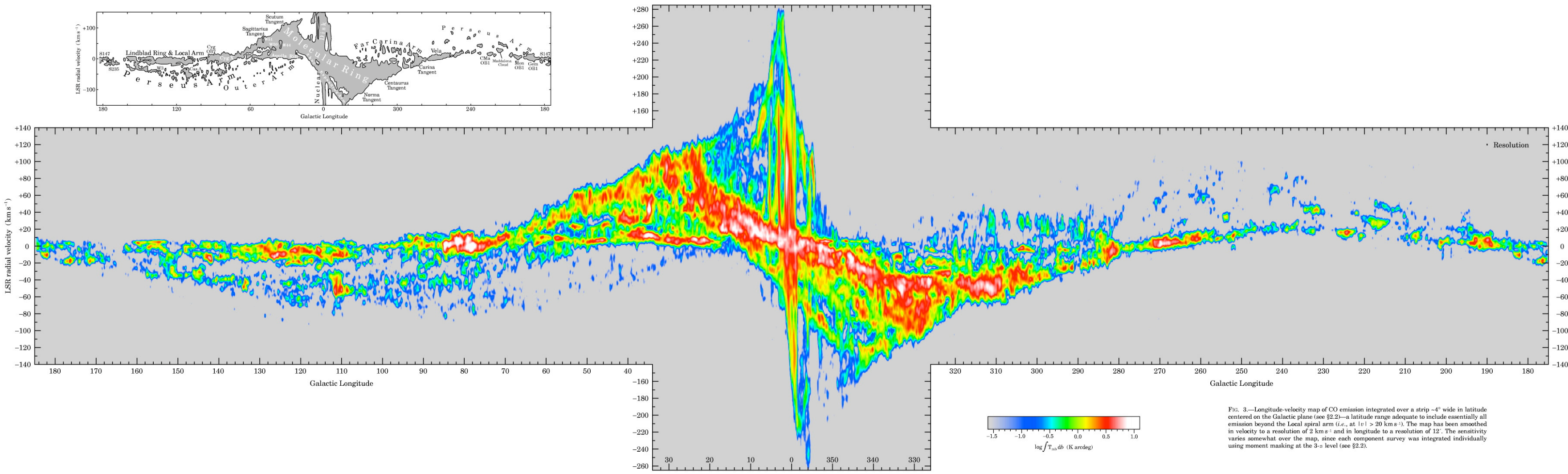
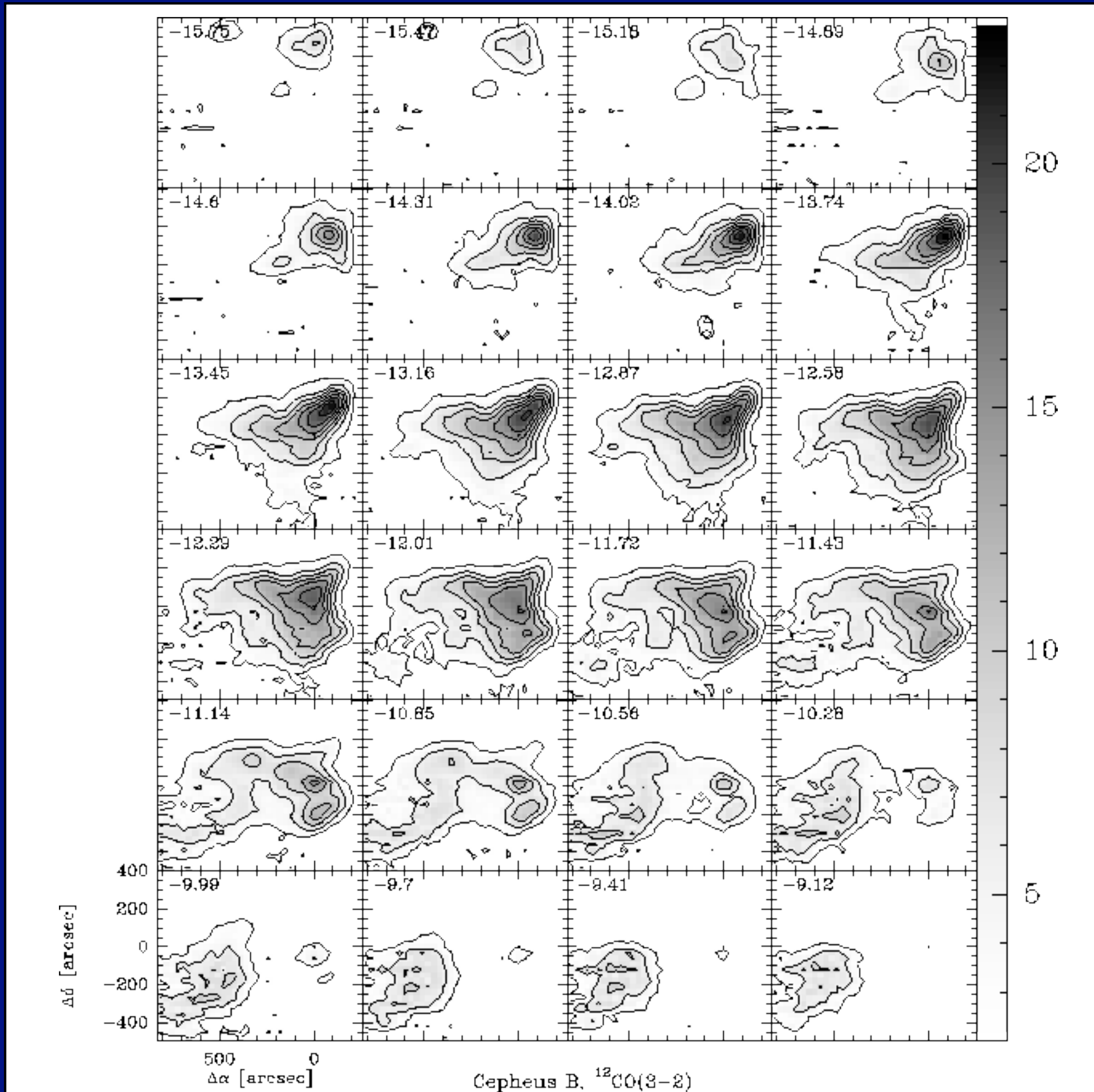
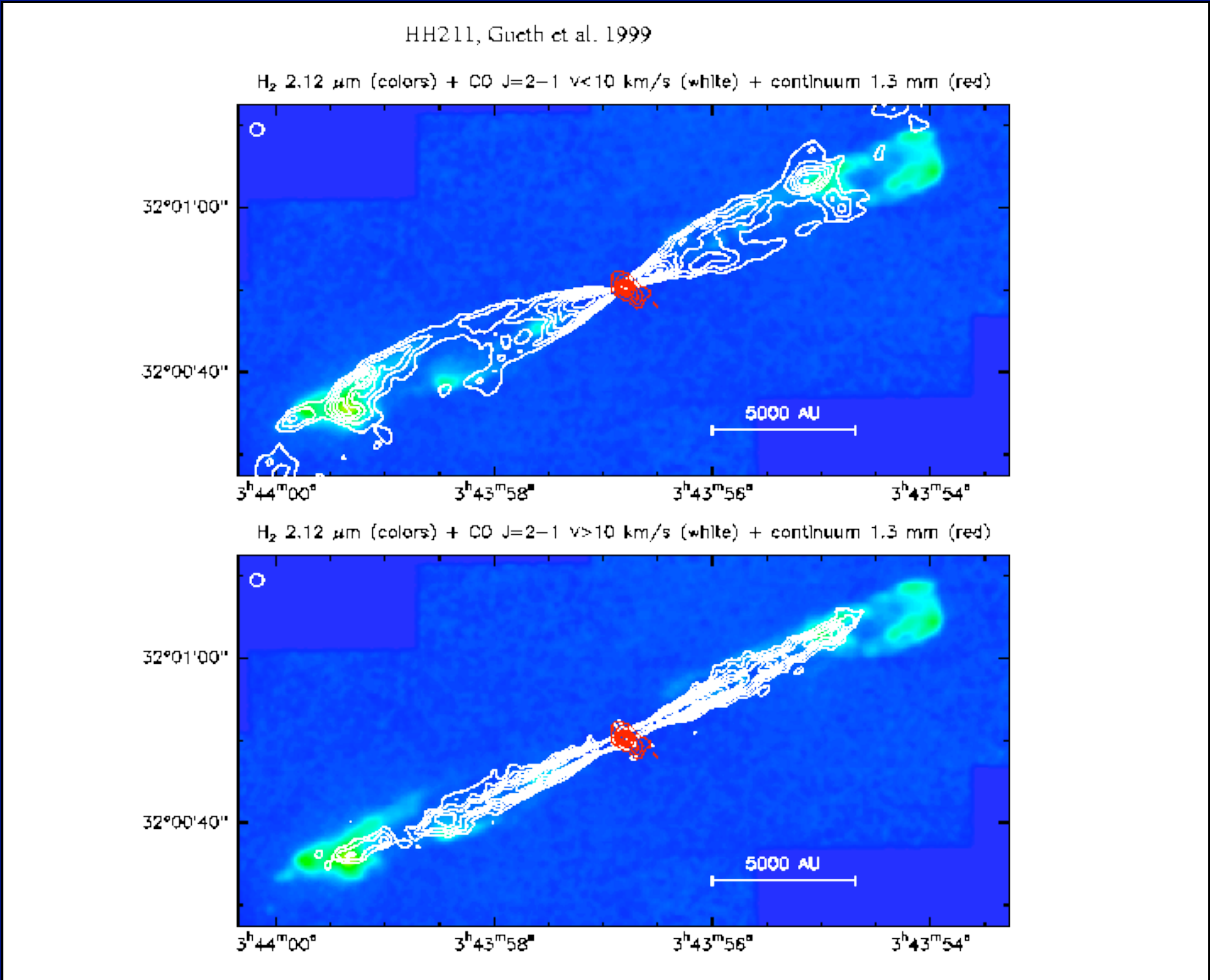


FIG. 3.—Longitude-velocity map of CO emission integrated over a strip ~4° wide in latitude centered on the Galactic plane (see §2.2)—a latitude range adequate to include essentially all emission beyond the Local spiral arm (*i.e.*, at $|v| > 20$ km s^{-1}). The map has been smoothed in velocity to a resolution of 2 km s^{-1} and in longitude to a resolution of 12′. The sensitivity varies somewhat over the map, since each component survey was integrated individually using moment masking at the 3-s level (see §2.2).

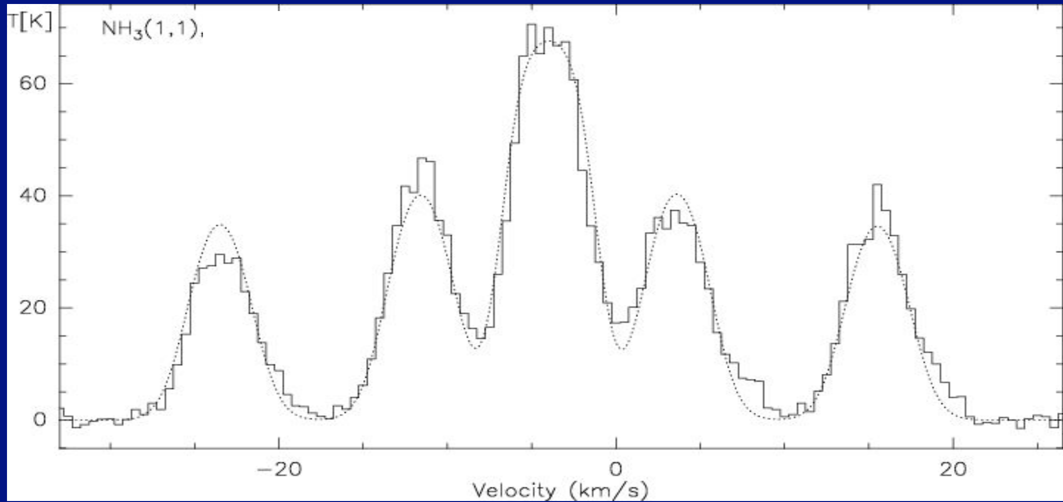
Applications II: Velocity structure of molecular clouds

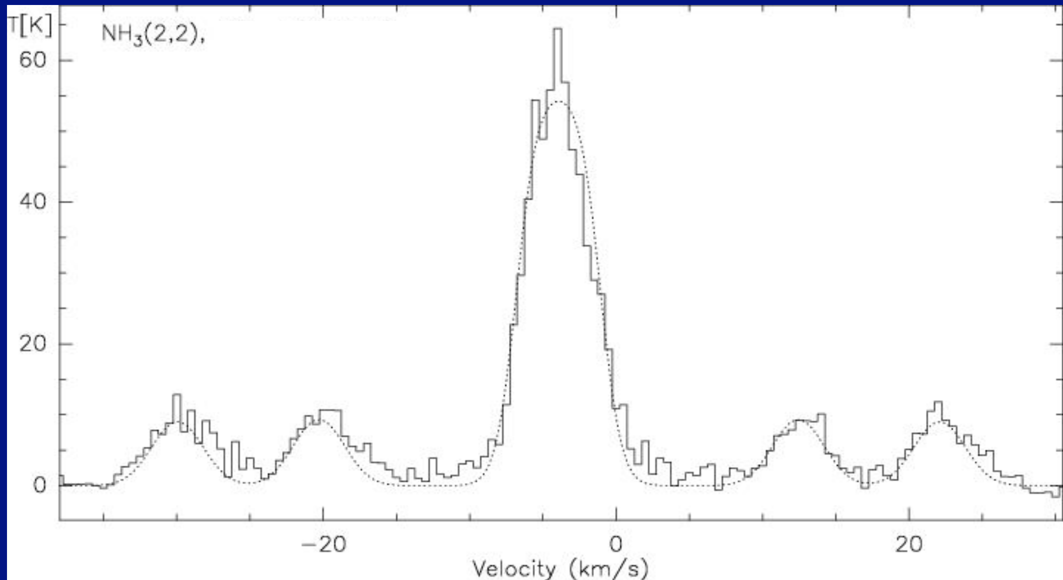


Applications III: Molecular outflows



Applications IV: Temperature estimates from NH_3





$$T_{kin} = T_{rot}\,(\tau_{11}\,\tau_{22}T_{11}T_{22})$$

Summary

- Main tools: Spectral line emission and thermal emission and extinction from dust (more on dust next week)

- Molecules interesting for themselves and chemistry

- However, also extremely useful to trace physical processes.

- Molecules deplete on grains at low temperatures

- Discussed main cooling and heating processes

- Discussed basic line radiation transfer and column density determination

- What causes line broadening?

- A few applications

Next week more about dust!

Sternentstehung - Star Formation

Sommersemester 2009

Henrik Beuther

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More Information and the current lecture files: http://www.mpia.de/homes/beuther/lecture_ss09.html
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