COLD ATOMIC HYDROGEN, NARROW SELF-ABSORPTION, and THE AGE OF MOLECULAR CLOUDS

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Motivation and Outline

- Timescale of star formation is of critical importance for understanding galactic & chemical evolution
- Probes are sorely lacking, especially for early phases of the process
- Atomic hydrogen is of significant potential importance DESPITE the fact that stars form in molecular clouds
  - Some History
  - Narrow HI Absorption
  - HI – H_2 Conversion
  - Timescales for Cloud Evolution and Star Formation
  - Detailed Models & Future Prospects

Possibility of Detecting the 21cm Line of HI in Interstellar Space

CORNELL

Ned. T. Natuurk. 11, December 1945.

Radiogolven uit het wereldruim *)

door C. J. Bakker en H. C. van der Hulst

RADIO WAVES FROM SPACE, SUMMARY

1. *Reception*, by C. J. Bakker.

A short introduction mentions the sources of „noise" in a radio set and the current fluctuations of an antenna immersed in a black body radiation field. Observations at wavelengths smaller than ca 20 m show that radiation of extraterrestrial origin is received by the antenna.

By directional records taken by Jansky and others the source of this radiation is located in the Milky Way, the greatest response being obtained when the antenna points towards the centre of the galactic system. Data of maximum intensities observed at four different wave lengths are given.

2. *Origin*, by H. C. van de Hulst.

Radio waves, received from any celestial object — they being the far infra red portion of its spectrum — deserve attention. Observations of small objects are prevented by diffraction. The sun may be a measurable object for future instruments.

The radiation observed from our galaxy must be due to the interstellar gas, the stars being outruled by their small angular dimensions and the solid smoke particles being outruled by their low temperature.

The spectral emission of a homogeneous layer of ionised hydrogen is computed. The continuous spectrum arising from free-free transitions has the intensity of black body radiation at wavelengths larger than 6 m and has a nearly constant intensity at wavelengths smaller than 2 m, corresponding to a large and to a small optical thickness respectively. These intensities, shown in figure 2, agree with those computed by Henyey and Greenstein and tally fairly well with the observations. No better accordance is to be expected, owing to the unknown electron density and extension of the interstellar gas and to unsatisfactory data about the directional sensibility of the antenna.

Discrete lines of hydrogen are proved to escape observation. The 2.12 cm line, due to transitions between hyperfinestructure components of the hydrogen ground level, might be observable if the life time of the upper level does not exceed 4.10⁸ year, which, however, is improbable.

Reber's observation of the Andromeda nebula suggests a rather high electron density. A cosmological remark concludes the article. The low background intensity due to remote nebulae contradicts the Hubble—Tolman static model.

I. Ontvangst der radiogolven

door C. J. Bakker

Inleiding. Het „geruisch" van een radio-ontvanger.

Het is bekend, dat de luidspreker van een radio-ontvanger een geruisch kan laten hooren. Bijzonder duidelijk is dit waar te nemen,

*) Naar aanleiding van voordrachten voor het colloquium van de Ned. Astr. Club op 15 April 1944 te Leiden.

Van der Hulst (1944)

Translated from Astronomicheski Zhurnal SSSR, 26 (1948) 1, 10-14.

A MONOCHROMATIC RADIO EMISSION OF THE GALAXY AND THE POSSIBILITY OF OBSERVING IT

I. S. Shklovski

In transitions between components of the hyperfine structure of the ground-state of interstellar hydrogen atoms, there is generated a monochromatic radio emission of frequency 1421.3 megacycles (λ = 21 cm). The probability of the transition is calculated as $0.72 \cdot 10^{-15}$ sec^{-1}. The half-width of this emission-line is due to the Doppler effect and is equal to $\Delta\nu_D = 4 \cdot 10^4$ sec^{-1}. The optical thickness of the interstellar hydrogen for this monochromatic radio emission is small. The intensity of the line λ = 21 cm is some tens of times greater than that of a band $2\Delta\nu_D$ wide of the continuous spectrum of the galaxy.

The experimental possibilities of detecting this emission are discussed. It is shown that with radio apparatus of present-day sensitivity, the said emission will be detected if the gain of the antenna is greater than 65, a value easily attainable.

It is further shown that no monochromatic radio emission is to be expected from other interstellar atoms.

The molecules CH, CH$^+$ and OH may, give a monochromatic emission (for OH, λ = 9.54 cm), generated in transitions between the Λ-doubling components of the rotational state. This emission may be detected.

A study of the intensity-distribution of the monochromatic radio emission over the sky will yield highly important information on the physical state of the interstellar gas.

The probability that a monochromatic radio emission of the galaxy might exist was first pointed out by van de Hulst [1]. Such an emission may occur in transitions between two very closely adjacent discrete atomic or mole-

Shklovski (1948)

Background of Harvard Experiment

- Harold Ewen, a graduate student at Harvard University, started PhD research with Edward Purcell, Professor of Physics, in 1950.
- Ewen had practical experience in physics and electronics, but little astronomy background.
- Based on literature, Ewen anticipated a "negative result" for 21cm line search.
- Project required external funding for equipment– that is similar to situation today, but style was significantly different:

AMERICAN ACADEMY OF ARTS AND SCIENCES
28 NEWBURY STREET
BOSTON

February 28, 1950

Dr. E. M. Purcell
Lyman Laboratory
Harvard University
Cambridge 38, Massachusetts

Dear Dr. Purcell:

I have the pleasure to inform you that the Council of the Academy at its meeting on February 8, 1950, voted to approve a grant of $500 from the Rumford Fund to you to assist in your microwave experiments on radiation from interstellar space.

Payment on this grant will be made to you in the manner you indicate upon your application therefor to the Treasurer of the American Academy of Arts and Sciences, 28 Newbury Street, Boston 16, Massachusetts.

Sincerely yours,

John W. M. Bunker

John W. M. Bunker
Secretary

JWMB:C

CORNELL

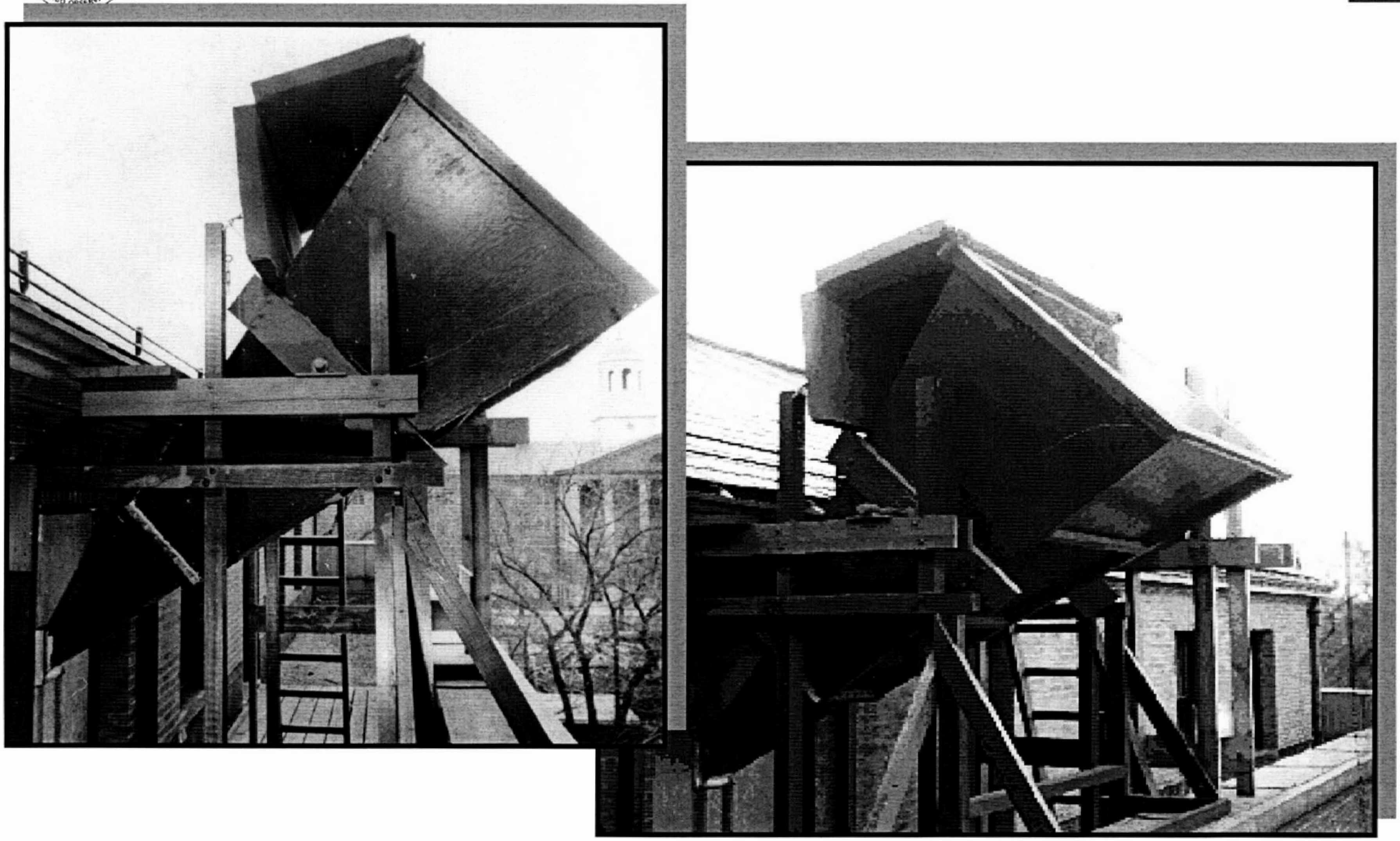
CHECK IS IN THE MAIL

FEBRUARY 28, 1950

PROGRAM KICK-OFF	**March 1950**
PROGRAM COMPLETE	**March 1951**

Harold Ewen

THE 21 CM RECEIVER AT THE TIME OF FIRST DETECTION OF THE SPECTRAL LINE IN 1951



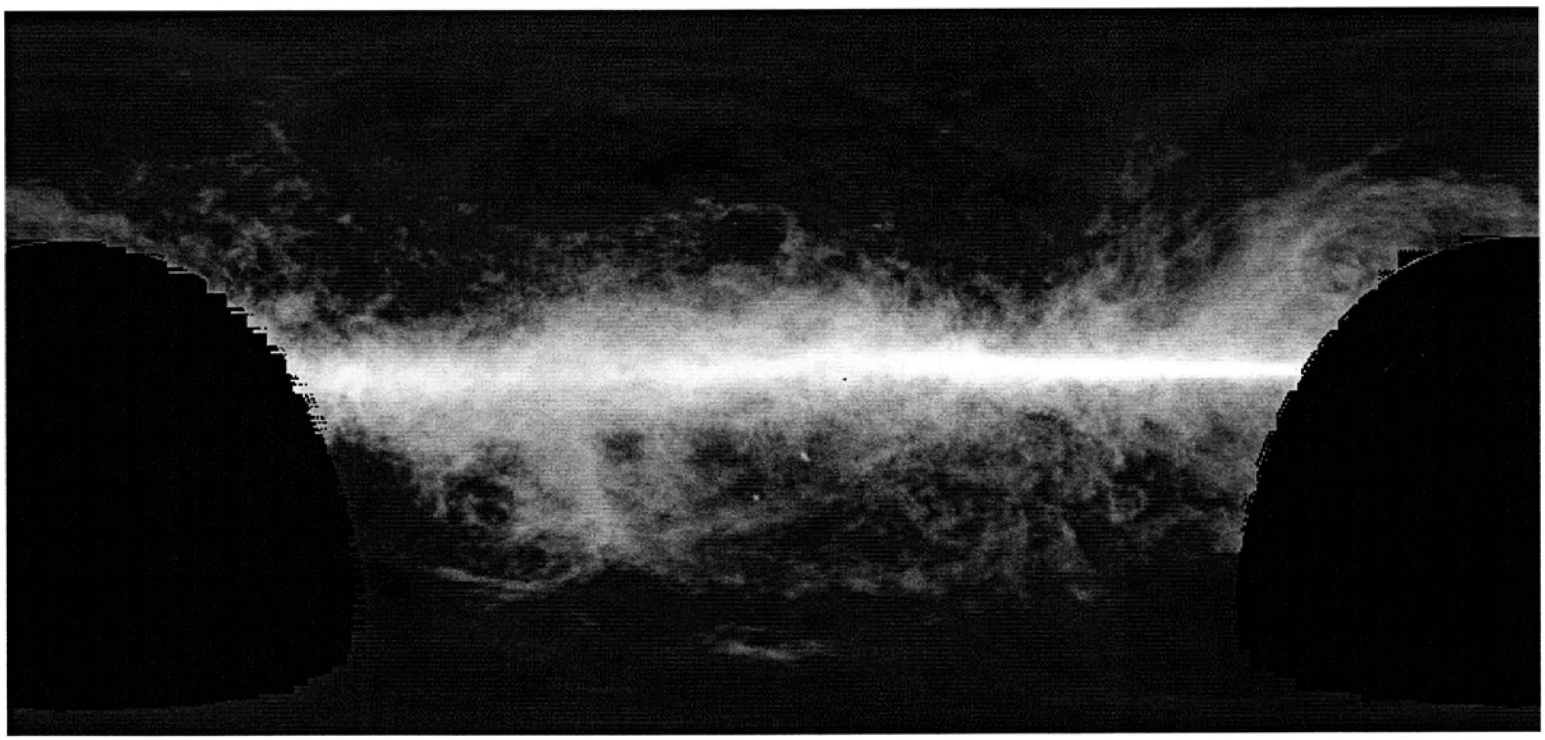
HORN ANTENNA ON FOURTH FLOOR PARAPET OF LYMAN
LAB AT HARVARD UNIVERSITY, CAMBRIDGE MA

Detection of the 21-cm Line of Atomic Hydrogen

- Discovered in 1951 by Ewen and Purcell (nearly simultaneous observations from Australia & Holland)
- Seen in EMISSION, which was not surprising since theories indicated that atomic gas in Milky Way would be warm (T ~ 100 K)
- Quickly became a powerful probe of the structure of Milky Way and of other galaxies and their distribution in the universe

The HI SKY

Warm Atomic Hydrogen in Emission



Leiden-Dwingeloo HI Survey (Burton & Hartmann 1997)

Angular Resolution ~ 0.5 deg.

1955: Clear Statement About Absorption Features

SOME FEATURES OF INTERSTELLAR HYDROGEN IN THE SECTION OF THE GALACTIC CENTER

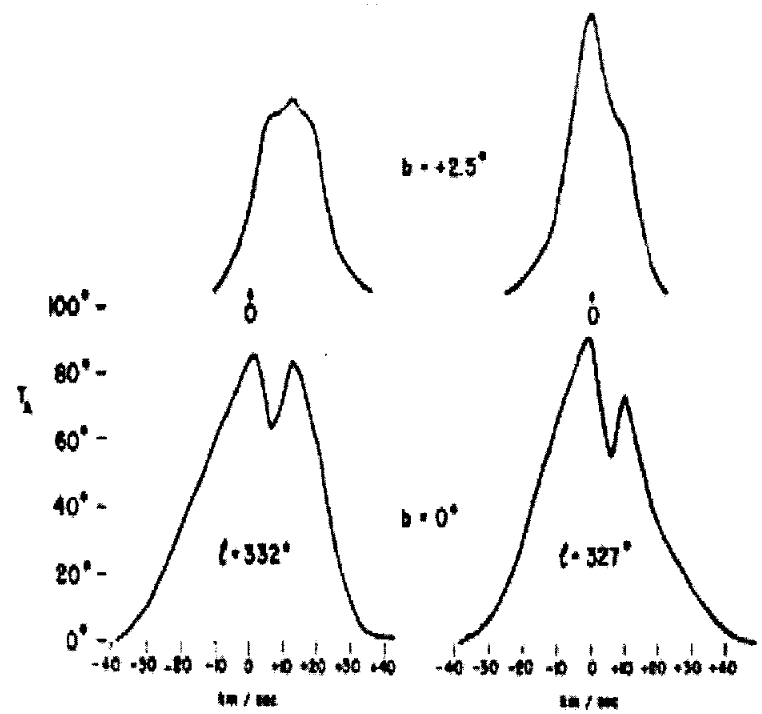
DAVID S. HEESCHEN*
Harvard College Observatory

Received November 17, 1954; revised December 6, 1954

ABSTRACT

Several results of observations of the 21-cm line in the section of the galactic center are discussed. A general positive correlation between the amount of obscuration and the number of neutral hydrogen atoms is found. The root-mean-square random radial cloud velocity at high latitudes is found to be 4.4 km/sec. The profiles at low galactic latitudes show a complex nature, with double peaks and asymmetries, which in this direction cannot be due to galactic rotation. Two alternative hypotheses are suggested as an explanation. Some indications of systematic deviations from purely circular galactic rotation are found.

The present investigation of the 21-cm line in the section of the galactic center was undertaken to study the physical characteristics and distribution of hydrogen in this region. This particular section was chosen because the complicating effects of galactic rotation are small or absent here and because of the variety of problems that present themselves for this part of the sky. The high-latitude fields are dominated by the Ophiuchus dark-nebulae complex, which has many problems associated with it. For regions at low galactic latitudes, we are faced with the variety of problems related to the structure and motions of the inner parts of the Galaxy.



1960: Term "Self-Absorption" Used for the First Time

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SELF-ABSORPTION IN THE 21-CM RADIATION FROM GALACTIC NEUTRAL HYDROGEN

V. RADHAKRISHNAN

California Institute of Technology Radio Observatory
Owens Valley, California

I. INTRODUCTION

Narrow-band studies of the absorption by interstellar hydrogen of the continuum radiation from strong sources have, in many cases, revealed sharp features in the absorption profiles.[1,2] Unpublished observations by the writer on additional sources of fairly low equivalent surface temperature and those by Heeschen[3] and by Davies[4] suggest the existence of clouds of neutral hydrogen having temperatures well below 125° K, which is the generally assumed temperature of galactic H I regions. This is further substantiated by the present observation of a region in which self-absorption occurs due to hydrogen at a temperature certainly no greater than 60° K.

In 1969 the Association of HI Self-Absorption Features with Molecular Emission was proposed by Heiles

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"Neutral Hydrogen in Dust Clouds"
1969 ApJ 156, 493

HI absorption velocities agree with those of OH emission or absorption

"SELF-ABSORPTION" FEATURE

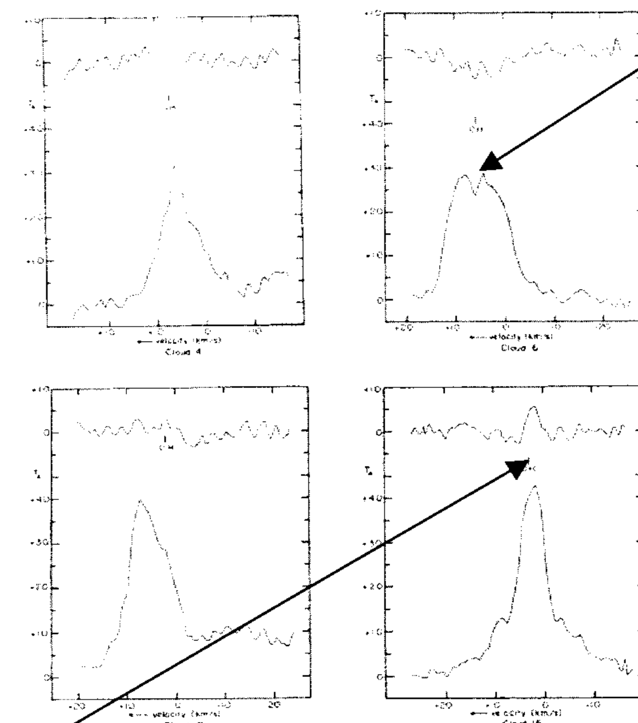
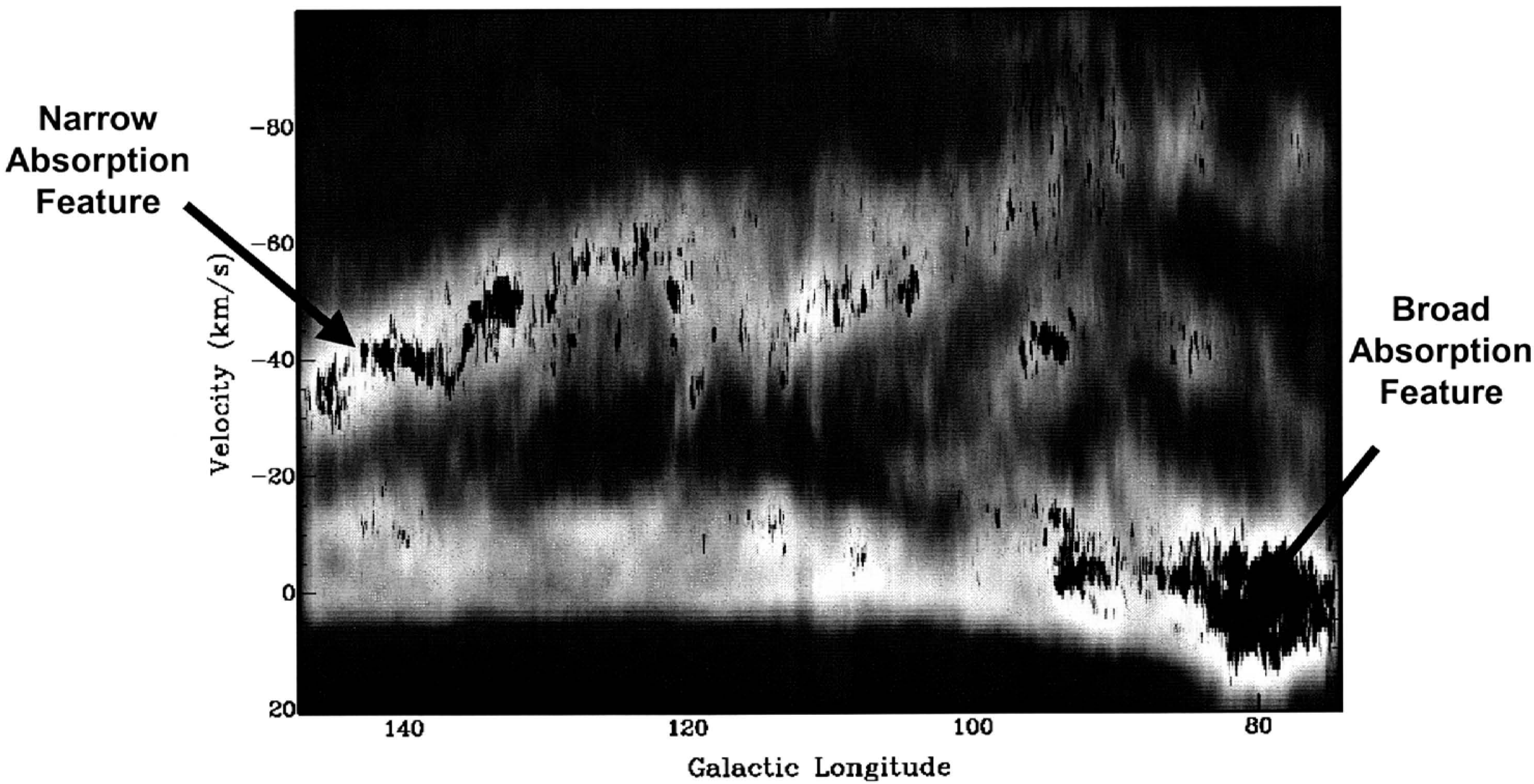


FIG. 5.—Some examples of profiles obtained with the 140-foot telescope. For each plot the bottom curve is the profile obtained on the dust cloud; the top curve is the difference between the profile on the dust cloud and the average of the profiles on the two comparison positions. The OH emission velocity is indicated for each object (Heiles 1968; Cudaback and Heiles 1969). Numbers refer to clouds in Table 2.

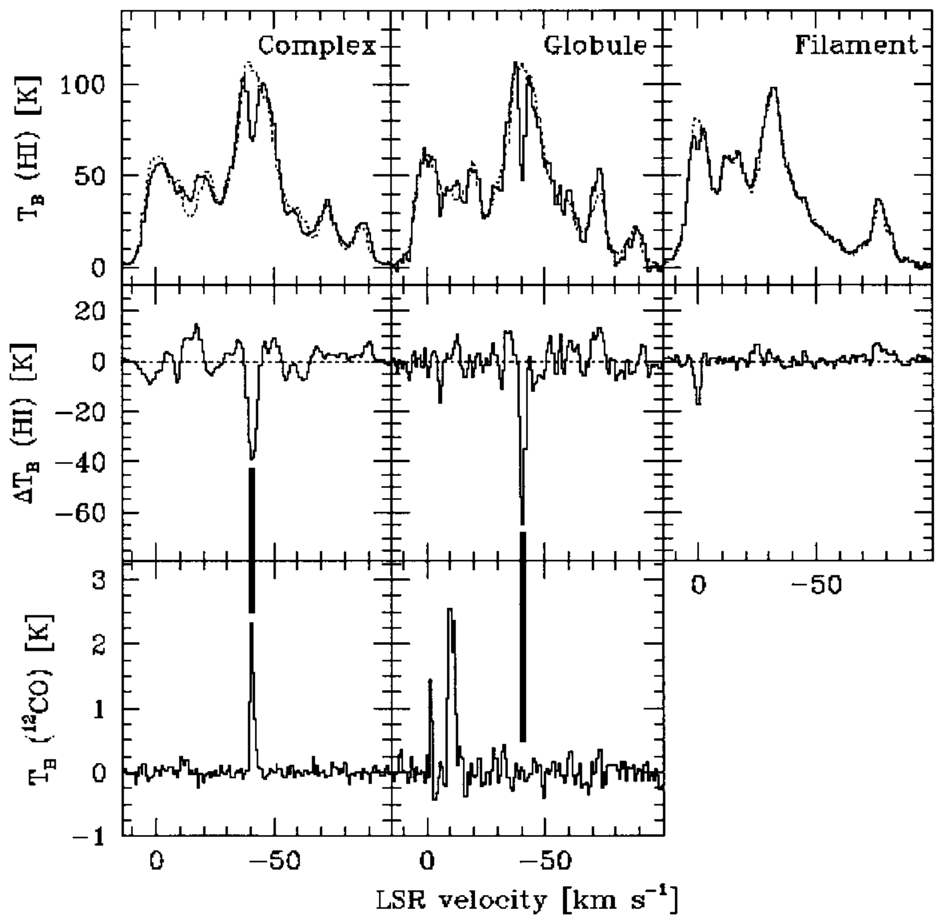
HI Self–Absorption (HISA) Has Been a Subject of Ongoing Interest

- Extensive surveys of dark clouds (e.g. Knapp 1974; van der Werf et al. 1988) were very suggestive
- Hampered by lack of required molecular data
- Large range of results in terms of HI/H_2 ratio
- Absorption features can be relatively broad (~ 5 km/s) to narrow (~ 1 km/s)
- Complex spectral and spatial structure when examined in large-scale studies

CGPS Survey of HI Shows Many Absorption Features



Large-Scale HI Absorption is Plausibly due to Quiescent Gas, but its Association with Molecular Gas is Problematic



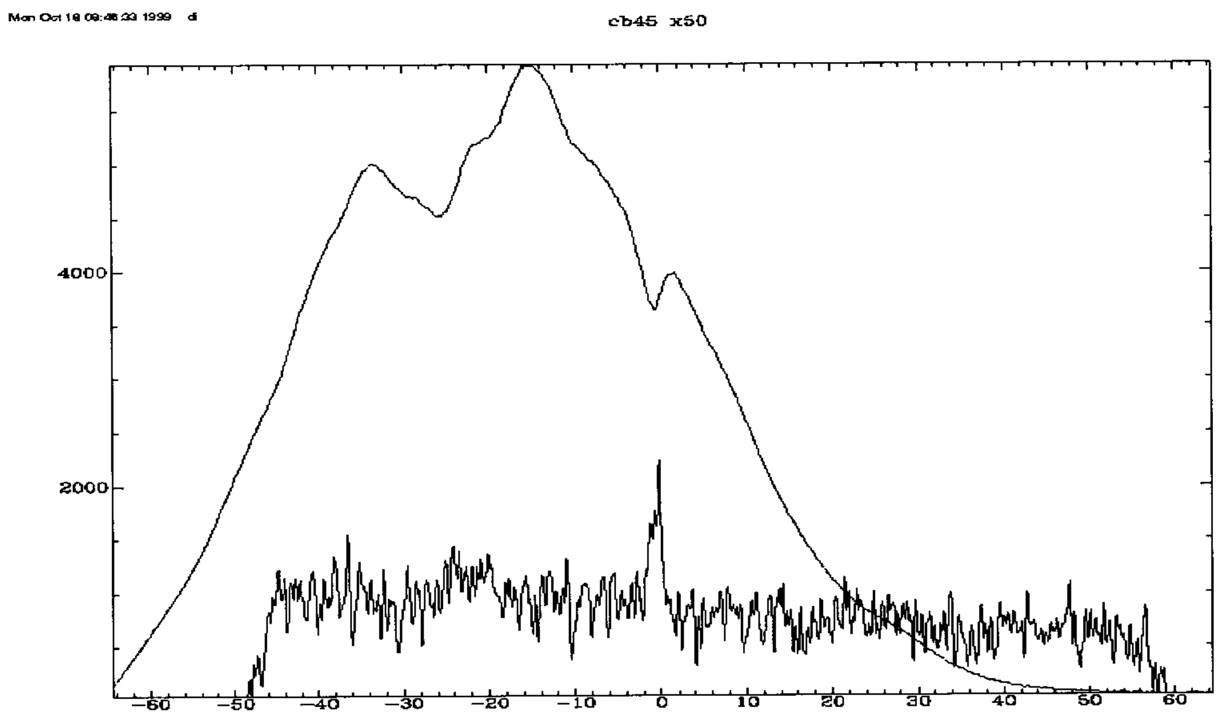
Velocity of HI absorption features often does not agree with v(CO) !

HI Self-Absorption and Star Formation

The connection between HI absorption and dark clouds is very enticing -

- Such molecular clouds are assumed to have *originated* as atomic clouds and *evolved* to higher densities and lower temperatures
- Ultimately may form dense cores which can collapse to form young stars
- This scenario is highly speculative but it is critical for overall understanding of the star formation process
- TIME SCALE is of particular interest

Molecular Emission (OH & CO) and associated Narrow HI Self-Absorption Features are Readily Observed in *Nearby* Molecular Clouds



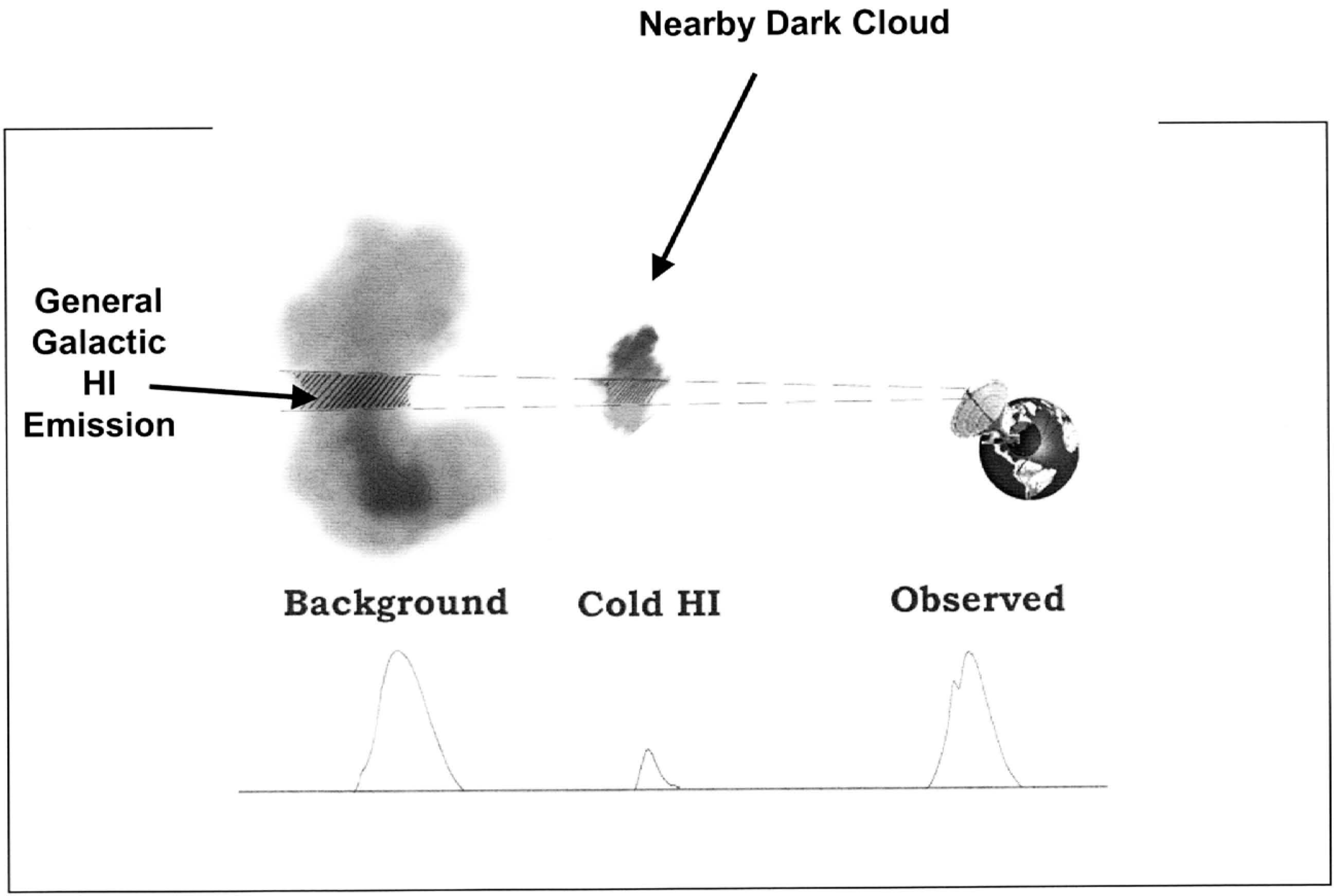
Arecibo data from Li & Goldsmith (2003)

Definition of HINSA: HI absorption with nonthermal linewidth comparable to associated molecular line widths

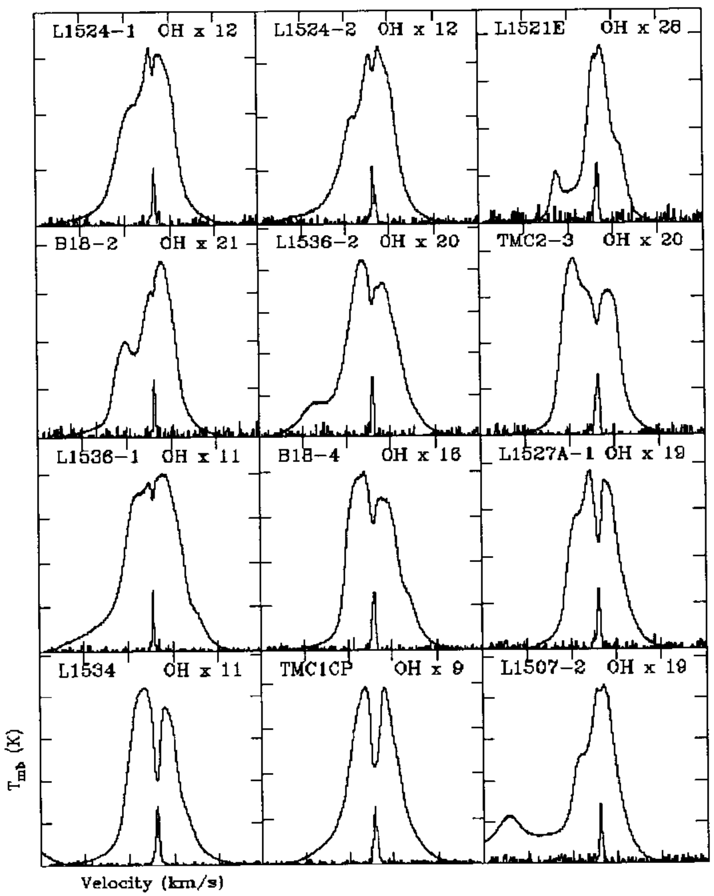
Atomic Hydrogen in Dark Clouds ?

- Previous studies suggested a relationship, but no clear demonstration of where the HI is relative to molecules, what its characteristics are, or what it can tell us about evolution of these regions
- Di Li (then Cornell, now CfA, soon JPL) and PFG undertook a systematic study of dark clouds in Taurus region
- 29 Dark Clouds selected from Lee & Myers (1999) catalog, having min. dia. = 3' and $0^{o} <$ decl. $< 35^{o}$ (observable from Arecibo)

The Situation as we Now See it:



HINSA Spectra in Arecibo Survey of Taurus (Li & Goldsmith 2003)

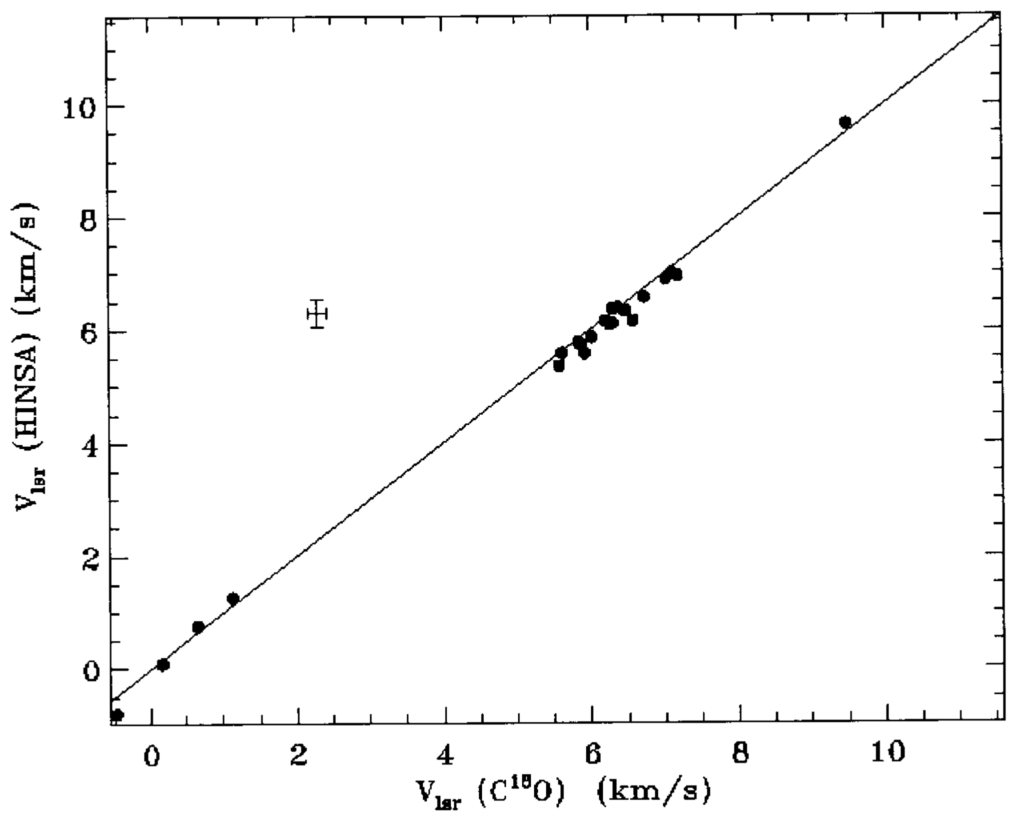


85% of Dark Clouds in Taurus exhibit HINSA

Simultaneous observations of OH with the Arecibo Gregorian make identification immediate and unambiguous

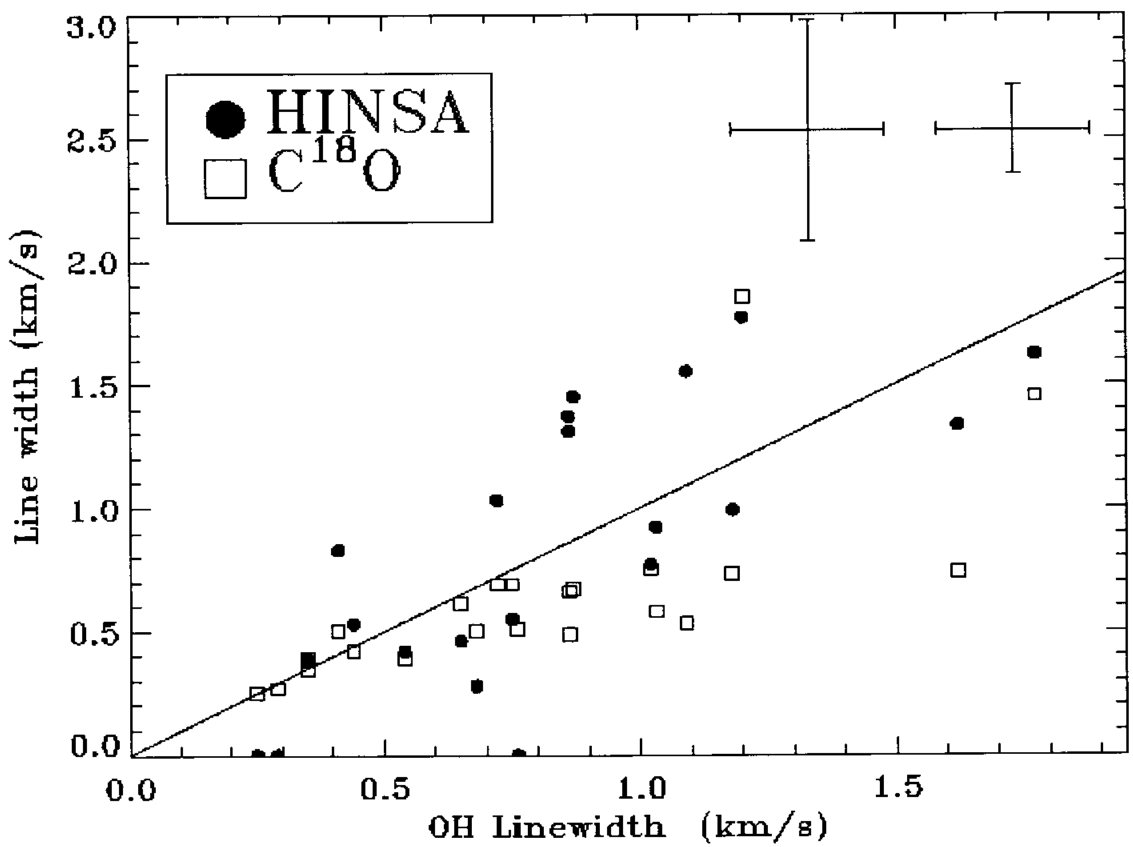
Key HINSA Facts (1)

Line Center Velocities agree extremely well with those of $C^{18}O$ (and also of ^{13}CO and OH)



Key HINSA Facts (2)

Nonthermal line widths are very close to those of ^{13}CO and correlate well with those of OH



Key HINSA Facts (3)

- Line Widths of the HINSA features are so narrow that they must come from very cold gas

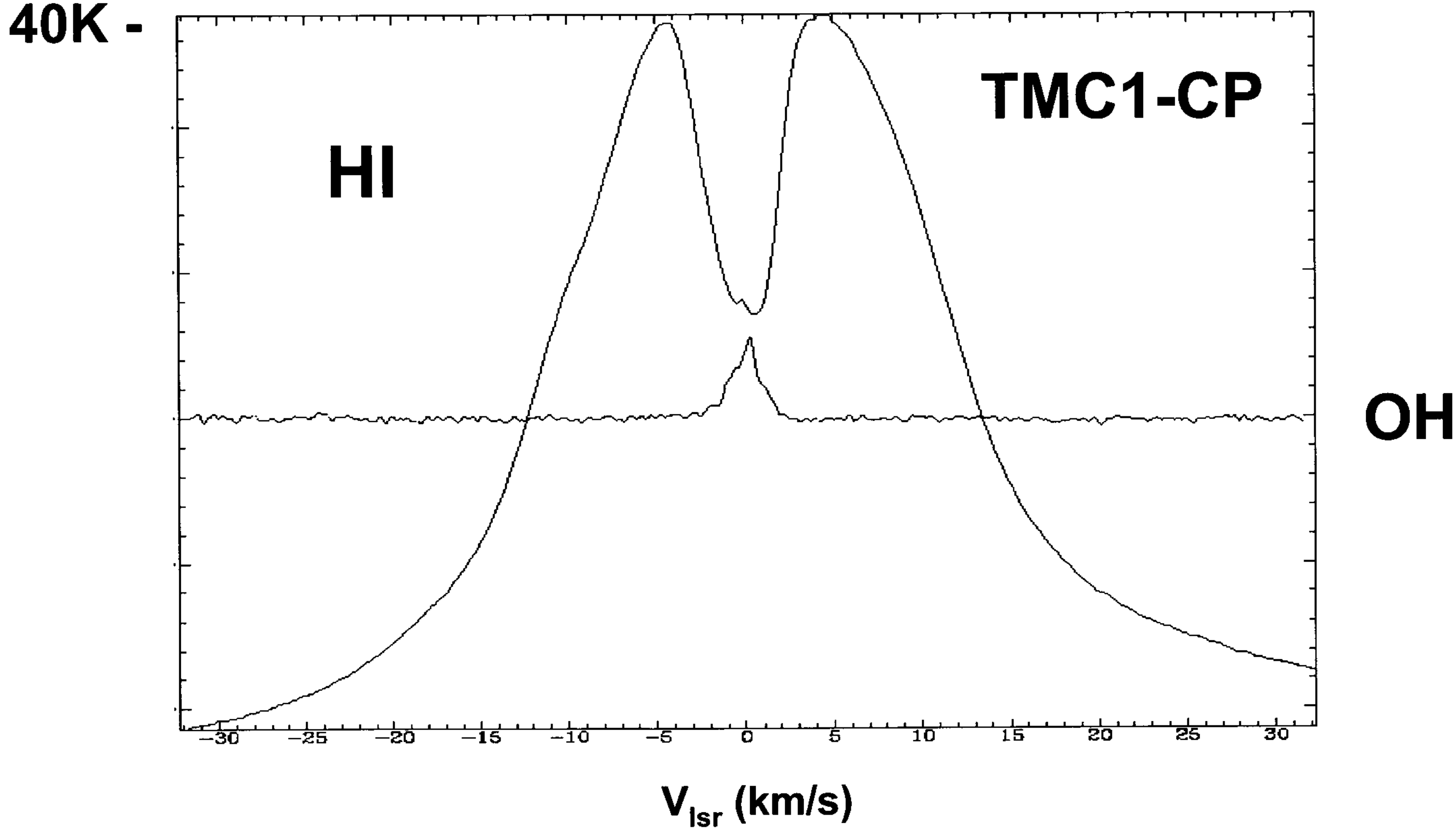
  45% @ T < 20 K!

  67% @ T < 40 K

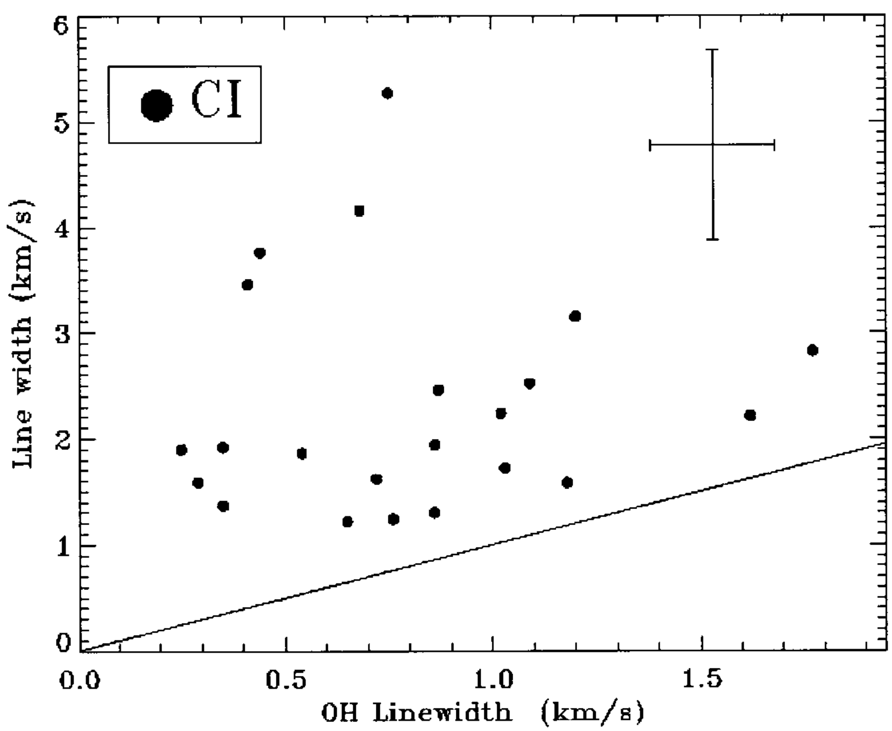
  Some of the wider line profiles are clearly the result of multiple velocity components so that individual profiles are narrower

Key HINSA Facts (4)

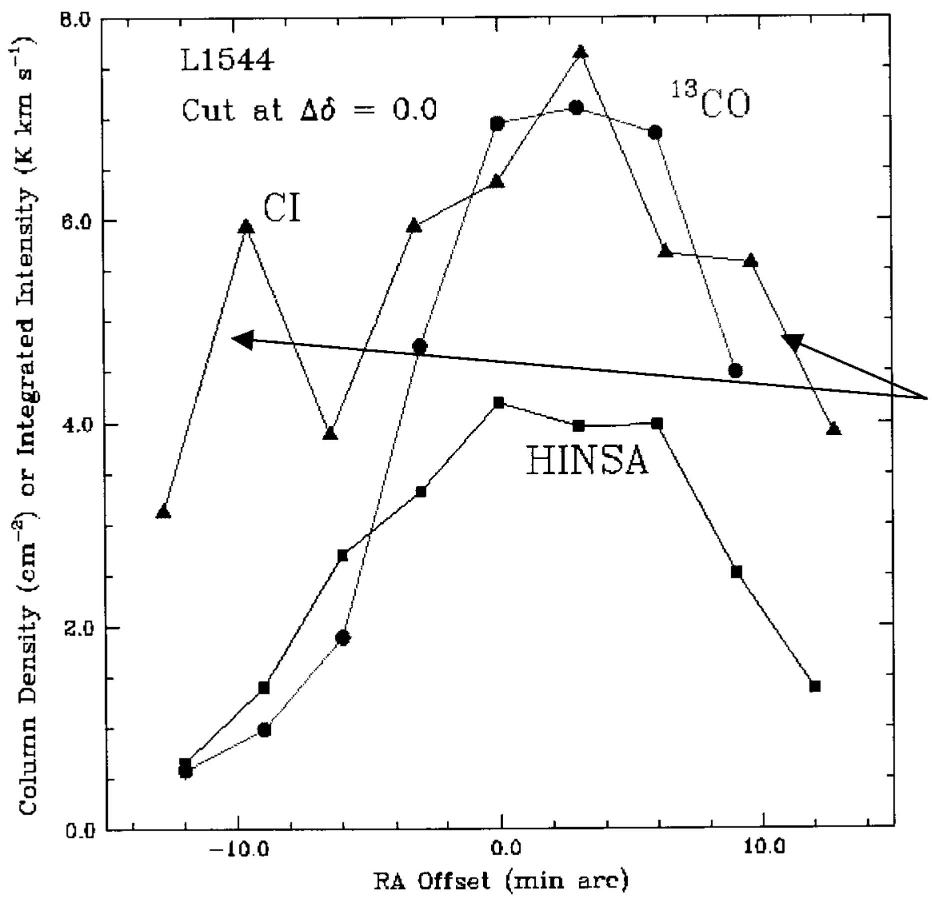
Line minima are so deep that in some cases the gas temperature must be below 20 K!



HINSA *not* Like CI Emission- CI Line Widths >> Those of Cold HI



HINSA *not* Like CI Emission- Cold HI *not* in "Onion Skin" PDR



CI 492 GHz data from SWAS satellite – emission is spatially more extended

Cold HI and Molecular Gas Morphology

- Distributions mapped in 4 clouds in Taurus using Arecibo and FCRAO. Data smoothed to 3.2' resolution

- HINSA & carbon monoxide distributions are very similar with closest agreement between cold HI and ^{13}CO

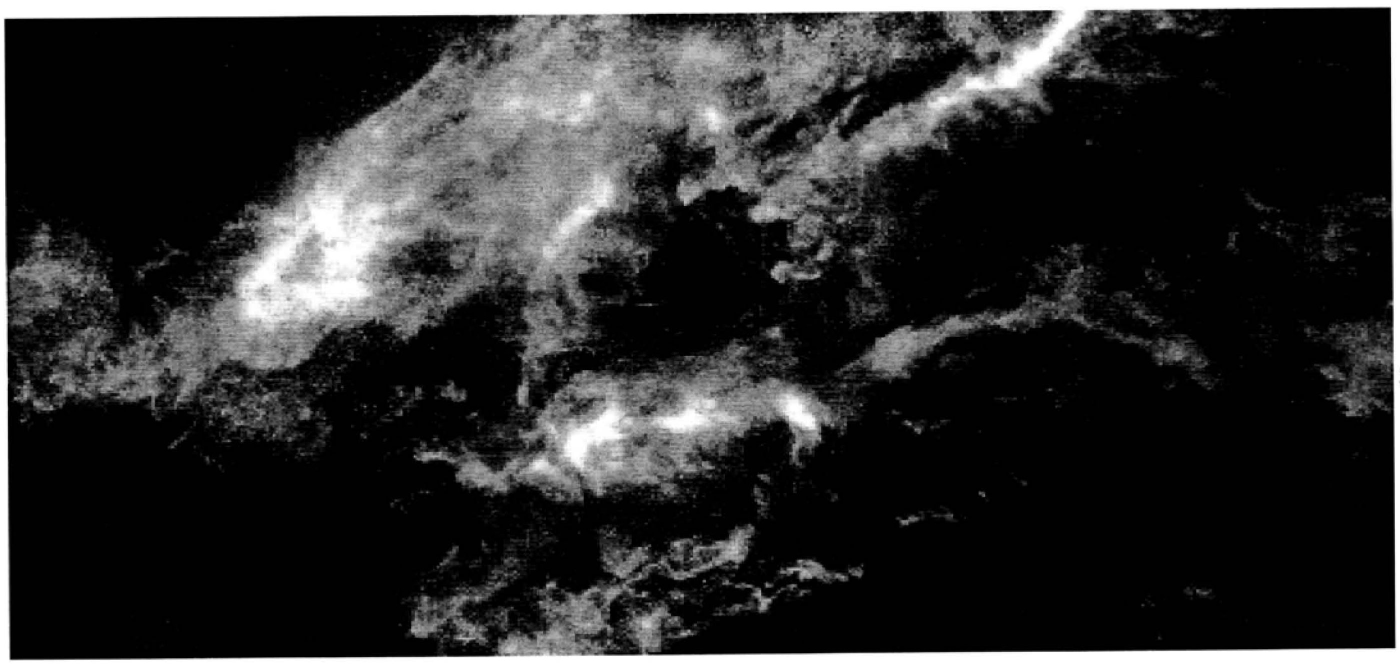
- Cold HI and OH column densities are not correlated in 3 of 4 clouds [exception is L1544] Distributions are similar overall, but not in detail

Key Characteristics of These Dark Clouds

- Kinetic temperature = 10 K
- H_2 Density = 1000 – 6000 cm^{-3}
- Size = 0.25 – 0.5 pc (FWHM)
- Visual Extinction A_v = 3 – 10 mag.
- Mass = 100 – 600 M_{sun}
- Embedded in the environment of large-scale Taurus molecular complex (A_v ~ few)
- Close to Virial Equilibrium

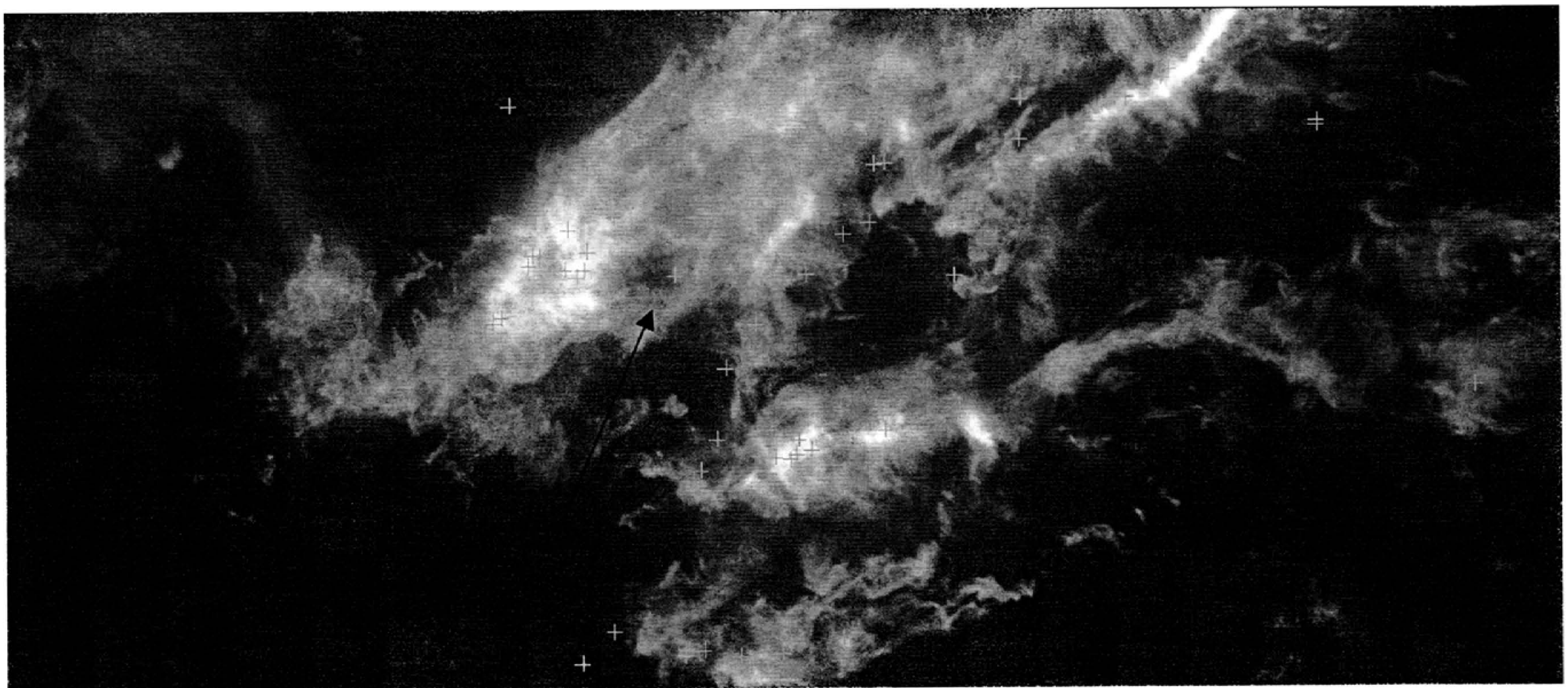
The Large – Scale Picture: ^{13}CO Integrated Intensity in Taurus FCRAO 14m w/ Sequoia Array: 55" res.

12 deg



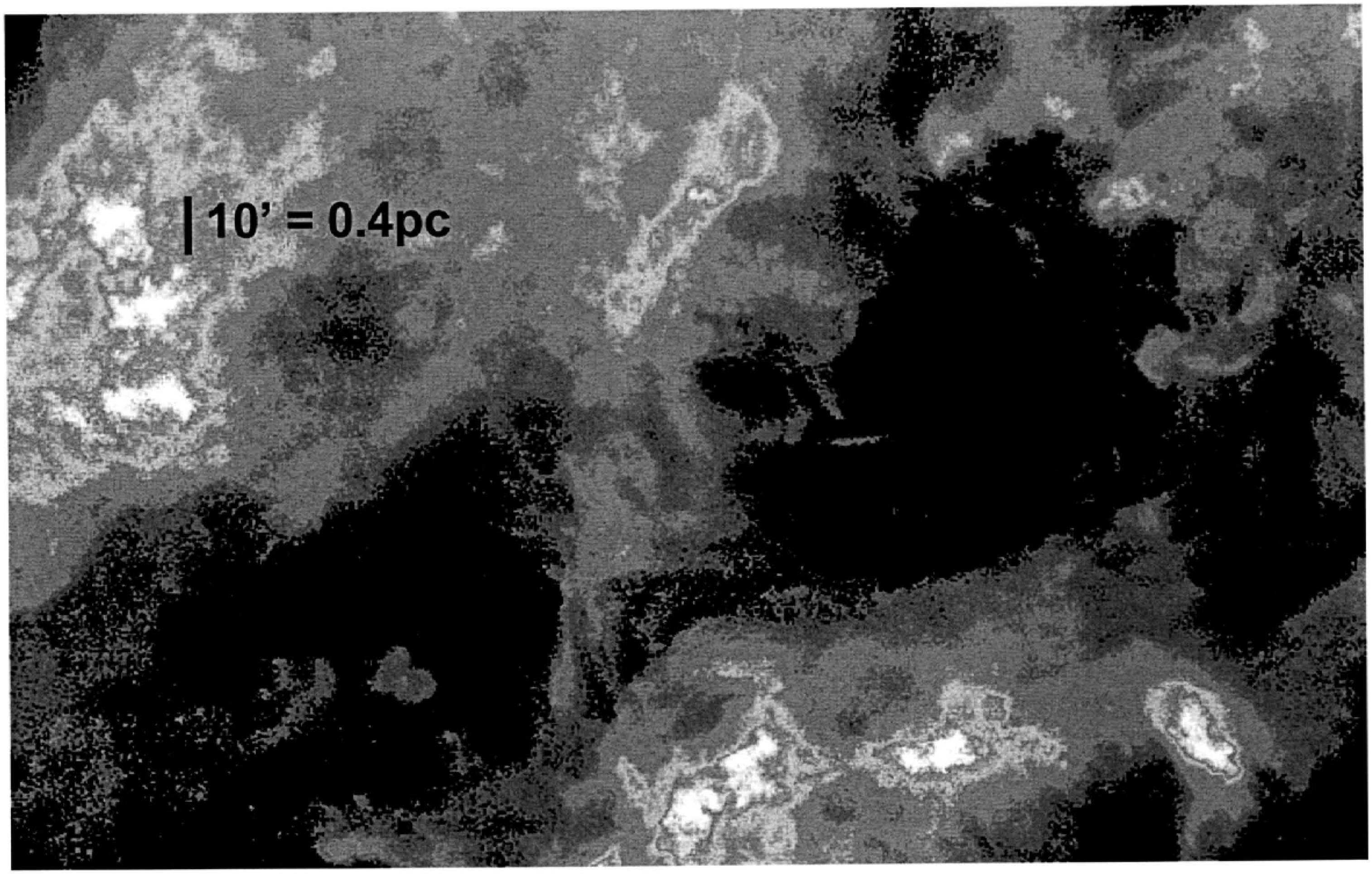
5 deg

Young Stars Found in Regions of Higher Density & Column Density

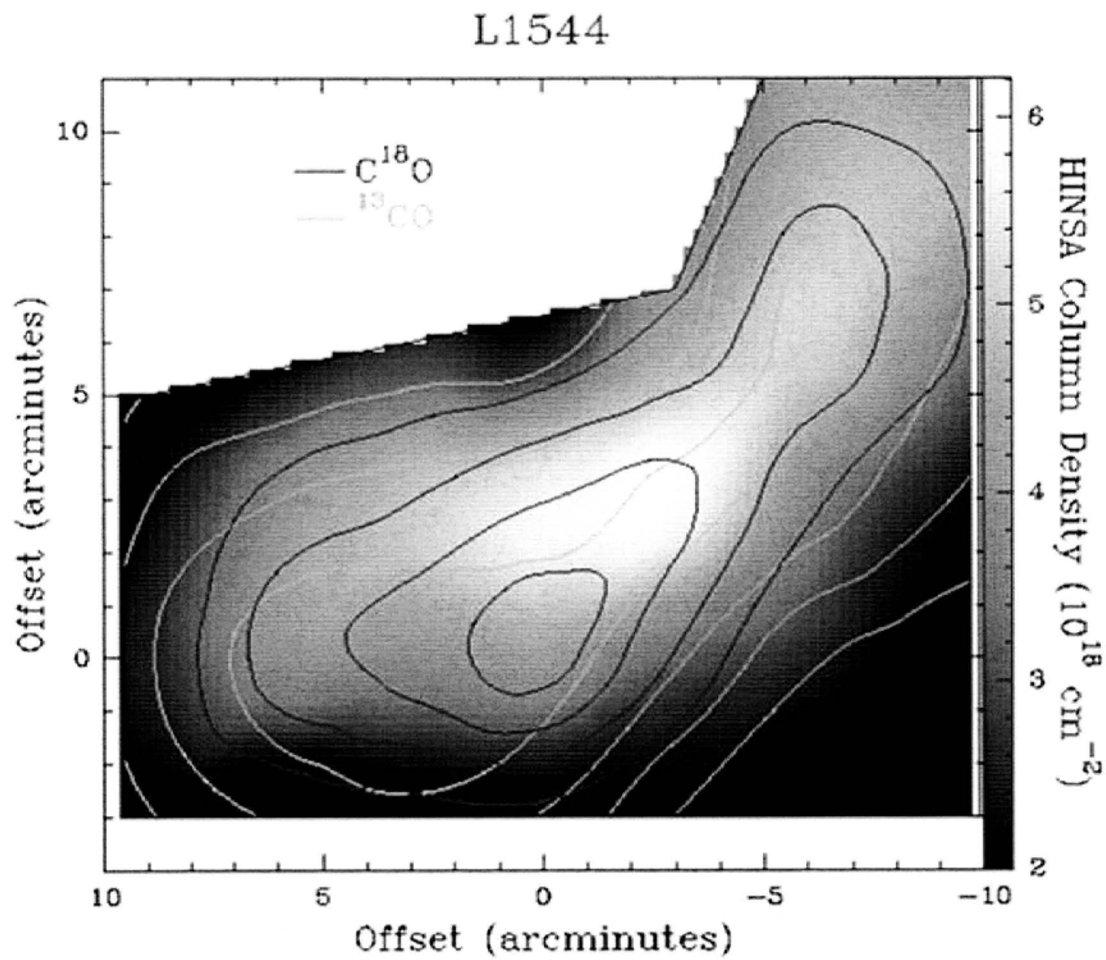


Embedded Low-Mass Star

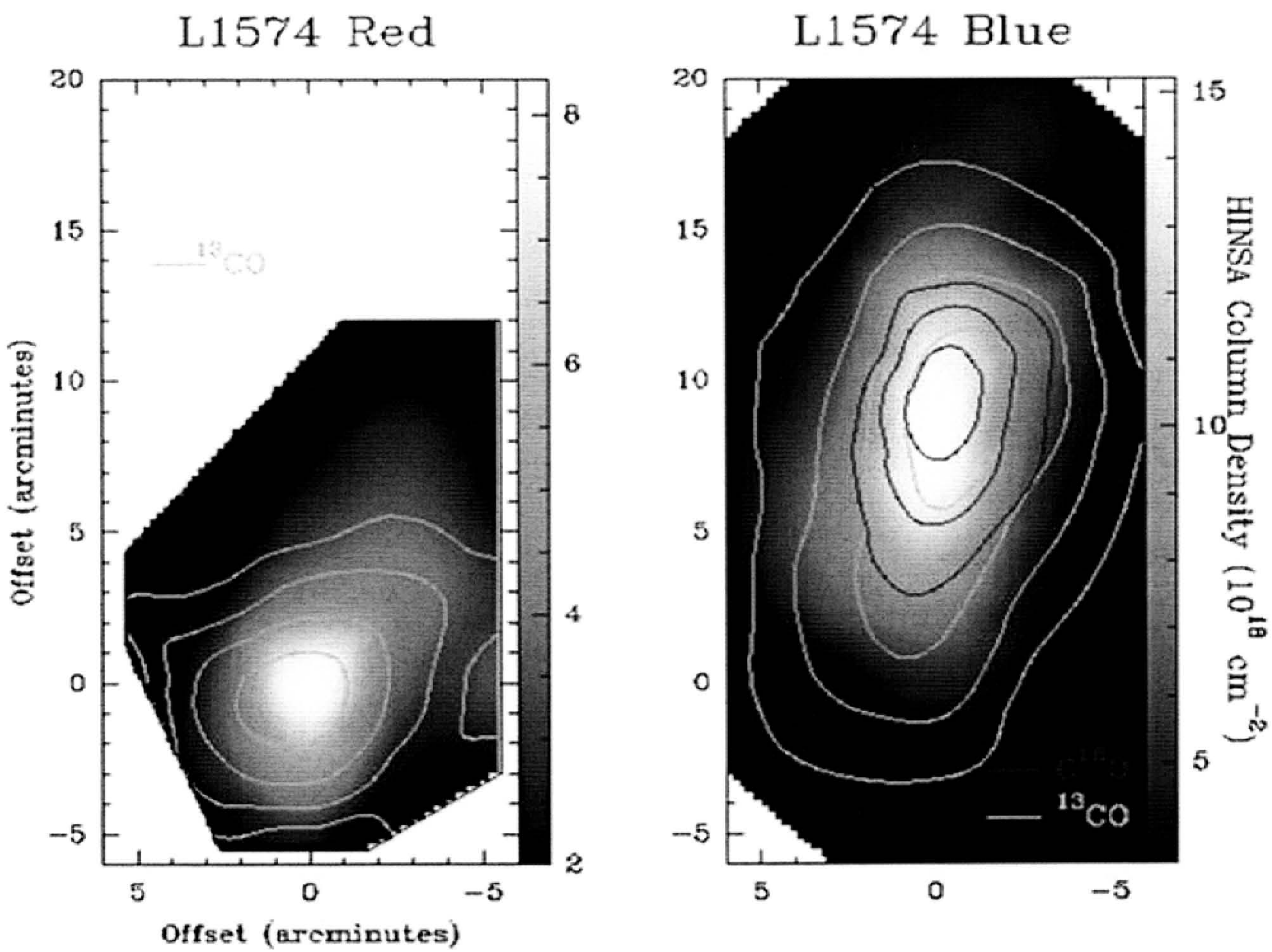
Detail Showing Individual "Clouds" Within Taurus Complex



HINSA (Color) & CO Isotopologues



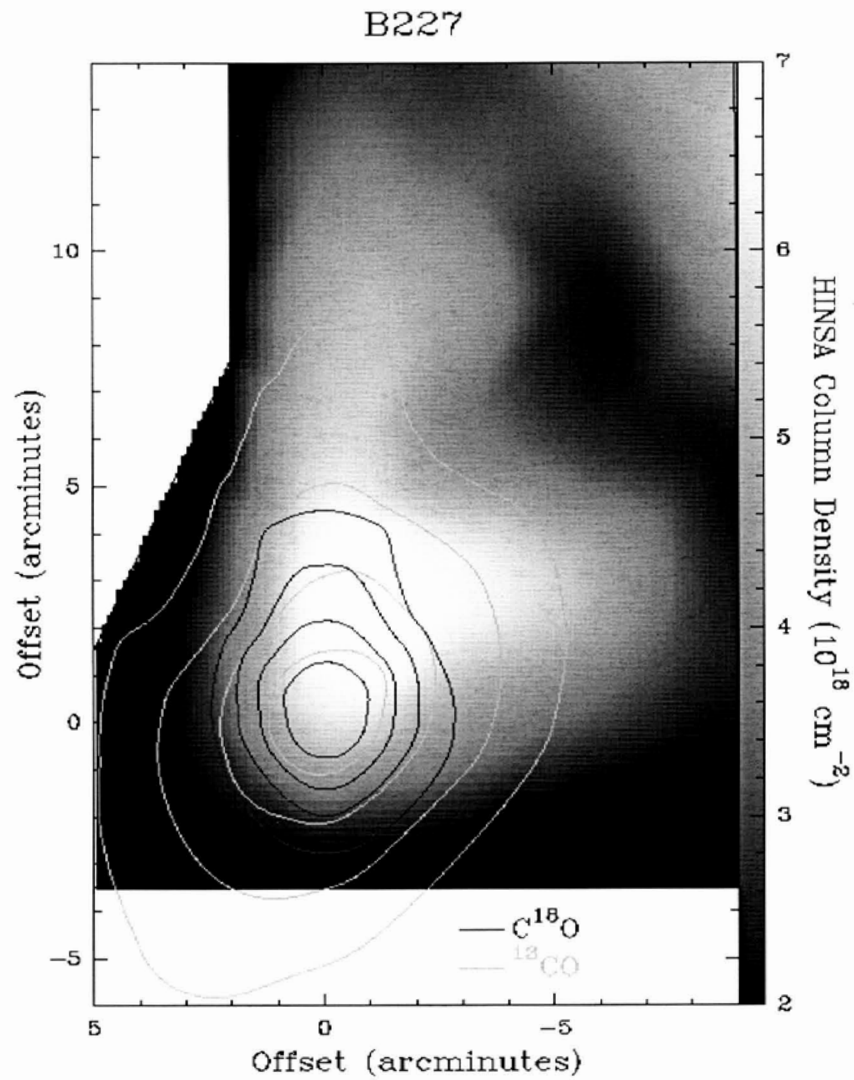
HINSA (Color) & CO Isotopologues

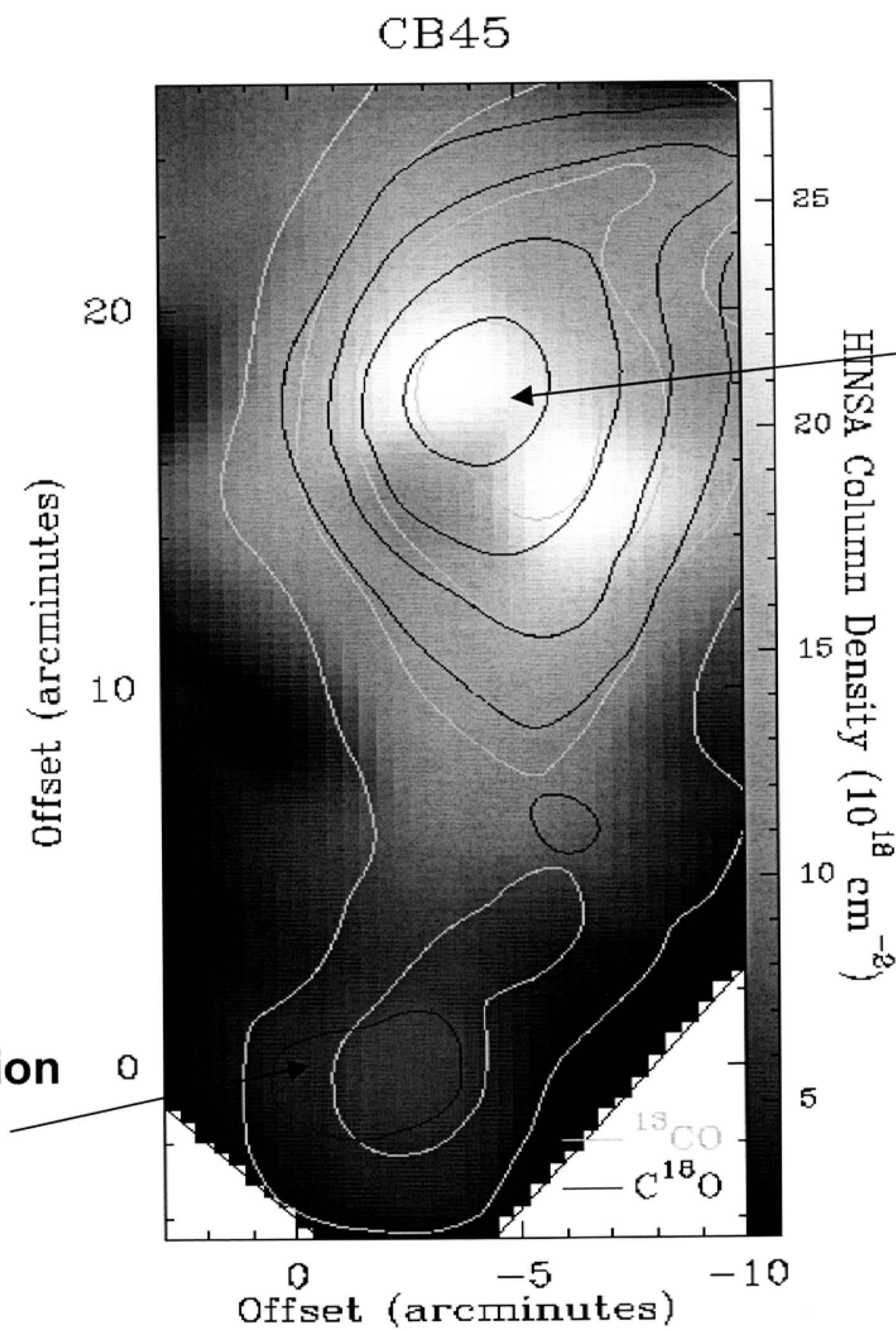


Two distinct velocity components

Each has HINSA and molecular feature

HINSA (Color) & CO Isotopologues



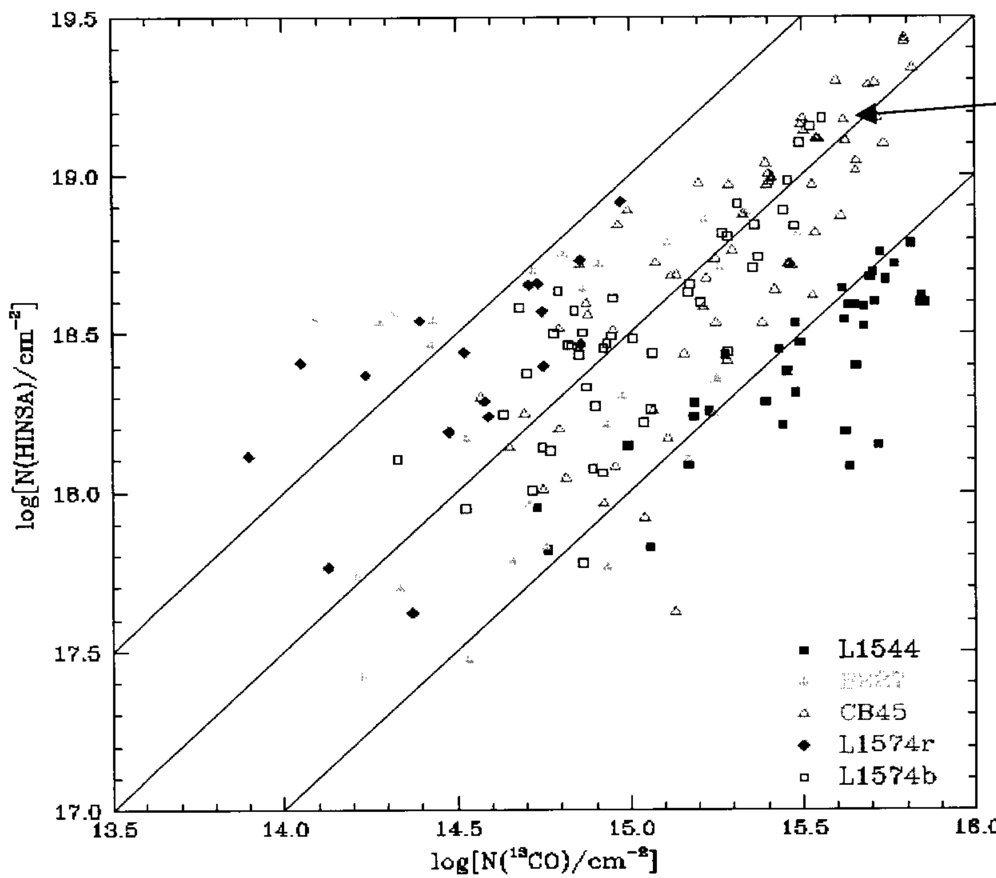


The "North" condensation was previously unknown and was found by mapping the HINSA and following up with ^{13}CO and C^{18}O

This morphology confirms close connection between cold HI absorption and molecular emission

nominal position in CB catalog

Correlation of Cold HI and ^{13}CO Column Densities



$N(HINSA) = 10^{3.5} N(^{13}CO)$

or

$N(HINSA) = 0.004 N(H_2)$

The HINSA Challenge

We wish to explain

- The characteristics of the HI Narrow Self-Absorption –
  - Where does it come from
  - Why are line widths so narrow
  - Why is it correlated with molecular column density, which traces $N(H_2)$
- The density and fractional abundance of the cold HI relative to H_2

The Cold Atomic Hydrogen

- HI Narrow Self-Absorption is produced by cold HI which is well-mixed with dominant H_2. Nonthermal linewidths ~ those of carbon monoxide isotopologues ^{13}CO and $C^{18}O$
- There may be additional atomic hydrogen in warm, outer "onion skin" but we discriminate against this observationally, since optical depth ~ 1/T
- This atomic hydrogen is at A_v of at least a few magnitudes, making photodestruction unimportant, at least at the present time

Model for HI and H_2 in Dark Clouds

These two species are intimately linked and together form closed system

HI formation = H_2 destruction

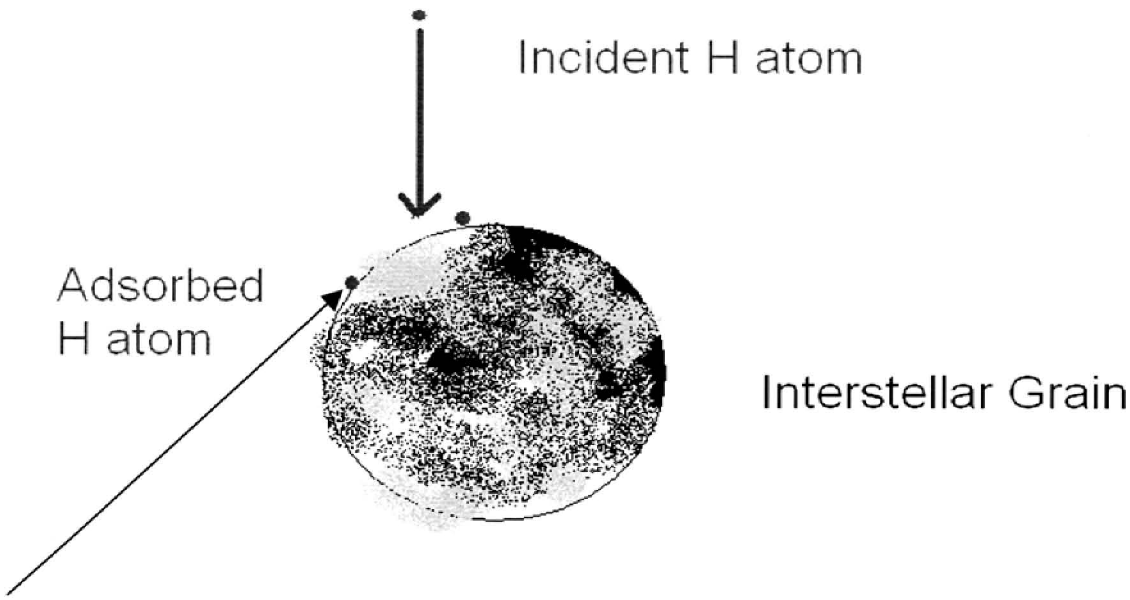
- Assume that since dust extinction is > few mag we can ignore photodestruction of H_2

- H_2 destruction (HI formation) is by cosmic rays at rate Dn_{H2} $cm^{-3}\,s^{-1}$; $D = 2.5\times10^{-17}\,s^{-1}$

H_2 Formation

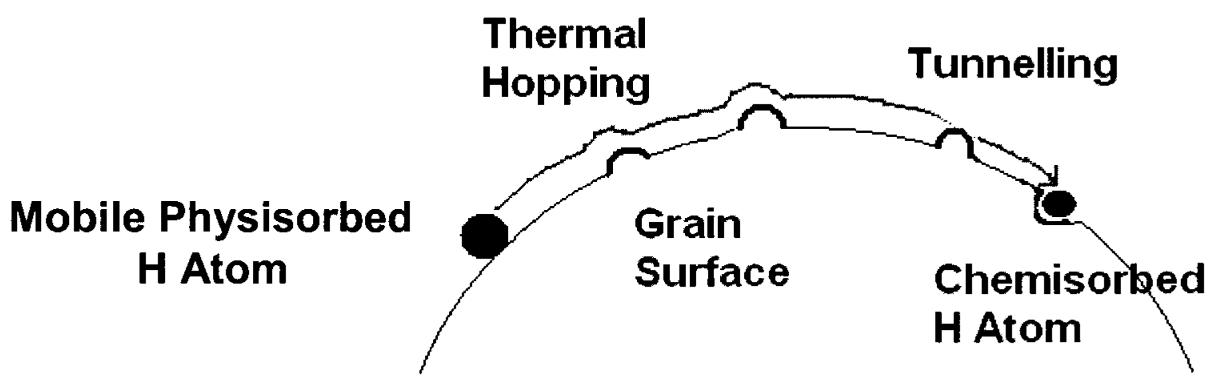
- Occurs on grain surfaces
- Grains described by MRN grain size distribution – small grains increase surface area per unit grain mass
- Incident H atom always finds a partner so formation rate of H_2 is proportional to the flux of H atoms and also to the density of grains

H_2 Formation on Grain Surface (1) Hydrogen Atoms Collide with Grain and Stick to Surface

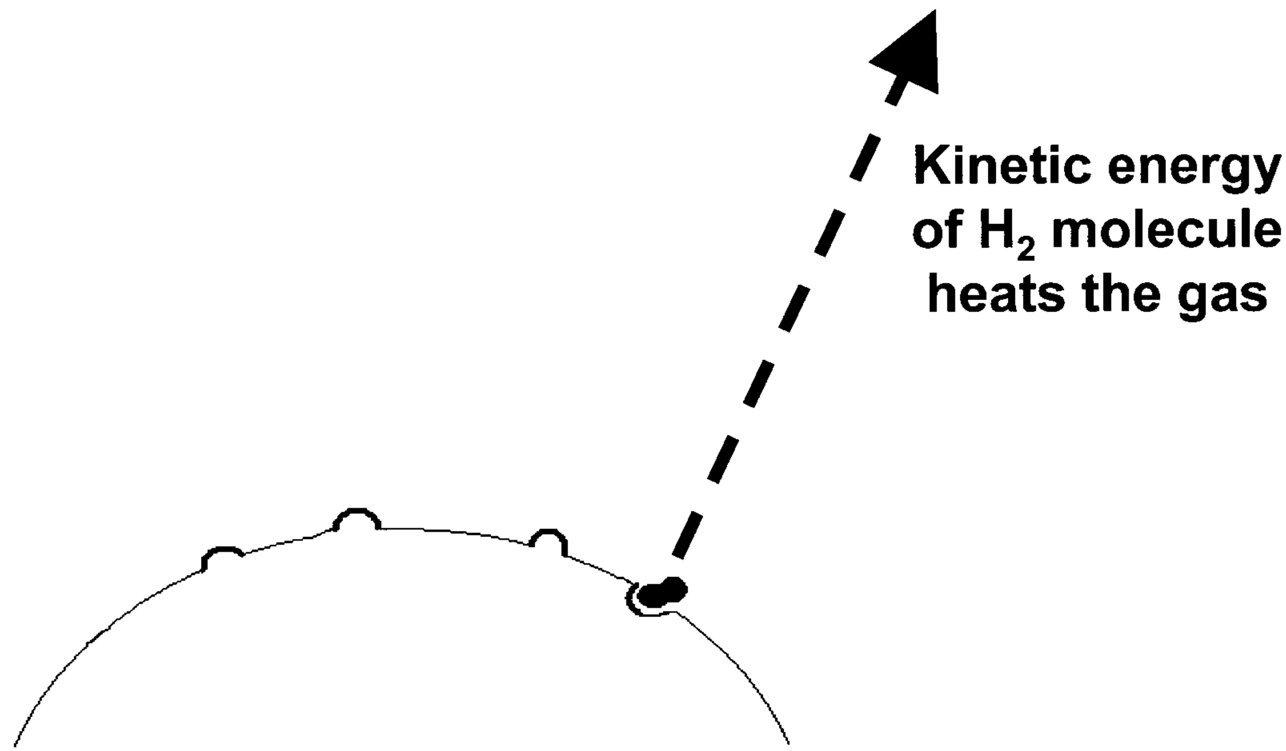


Adsorbed atom can be chemisorbed (immobile) or physisorbed (mobile)

H_2 Formation on Grain Surface (2) Mobile Grains "Explore" Surface via Thermal Hopping and/or Tunneling



H_2 Formation on Grain Surface (3) Two H-Atoms Form H_2 Molecule Binding Energy of H_2 Desorbs the Newly-Formed Molecule



Time-Dependent H_2 Density

H_2 density governed by a very simple differential equation:

$$dn_{H2}/dt = Fn_0\, n_{HI} - Dn_{H2}$$

with $n_0 = n_{HI} + 2n_{H2}$

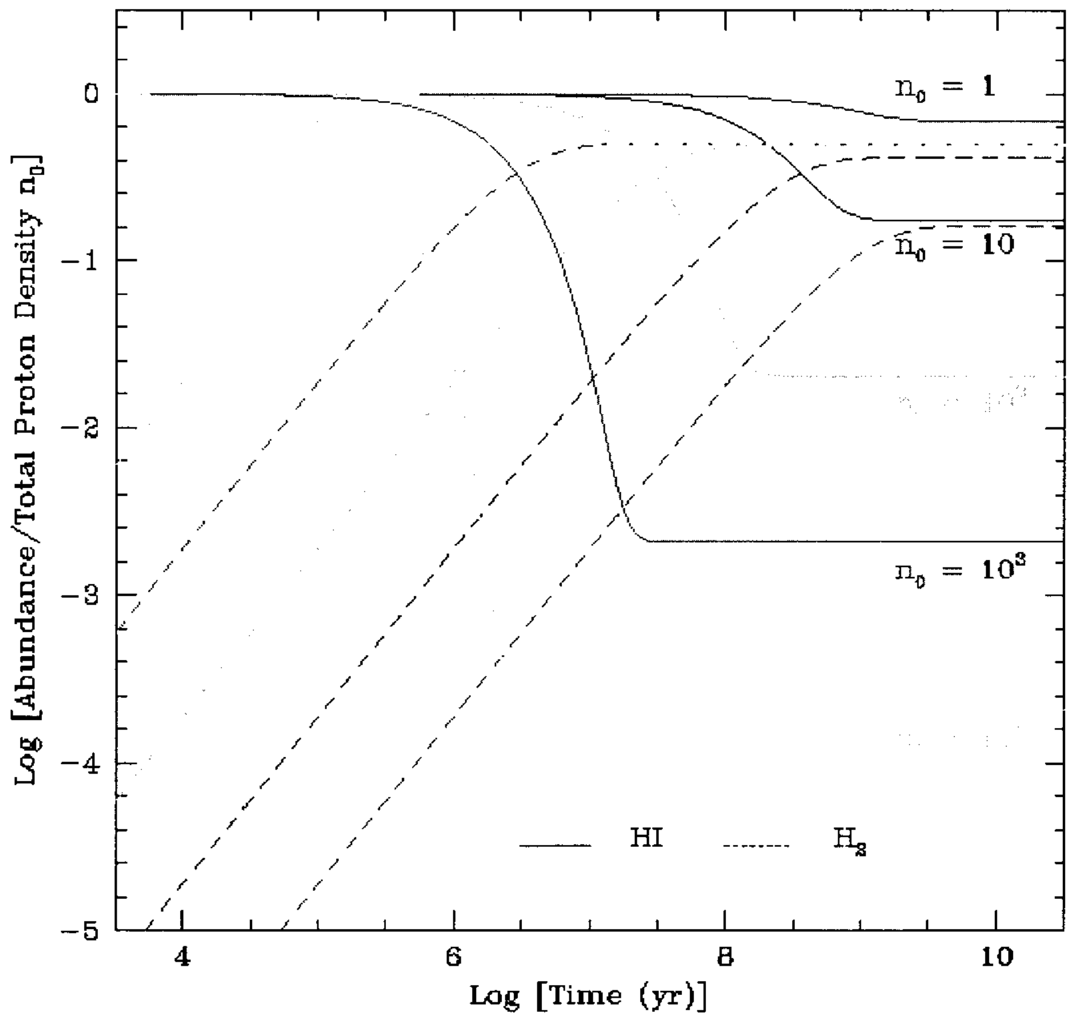
$F = 6 \times 10^{-18}\ cm^3\ s^{-1}$

Cloud Evolution and HI to H_2 Conversion

- Cloud is initially entirely atomic
- Assumed to be held in this state by photodestruction (low extincion)
- @ t = 0 an "event" (e.g. shock compression resulting in increase in A_v) terminates photodestruction and initiates HI to H_2 conversion
- Cloud evolves at constant density

Evolution of HI and H_2 Densities

(no photodissociation)



HI Fractional Abundances

Cloud	n_{HI}	n_{H2}	n_{HI}/n_o
	cm^{-3}	cm^{-3}	
L1544	3.0	3100	4.8e-04
B227	2.0	1000	1.1e-03
L1574r	3.9	800	2.4e-03
L1574b	5.9	1100	2.7e-03
CB45	6.0	1900	1.8e-03

H_2 densities from ^{13}CO

Abundance ratios from $C^{18}O$ are smaller by less than 50%

Key Parameters for HI to H_2 Conversion

Steady-state solution:

$$n(HI) = n_0 [1 + 2Fn_0/D]^{-1}$$

$Fn_0 >> D$ means $n(H_2) >> n(HI)$ so gas is largely molecular

Steady-state HI density:

$$n_{HI}^* = D/2F = 2.5x10^{-17} /2*6x10^{-18} = 2 \text{ cm}^{-3}$$

Time Scale for HI to H_2 Conversion

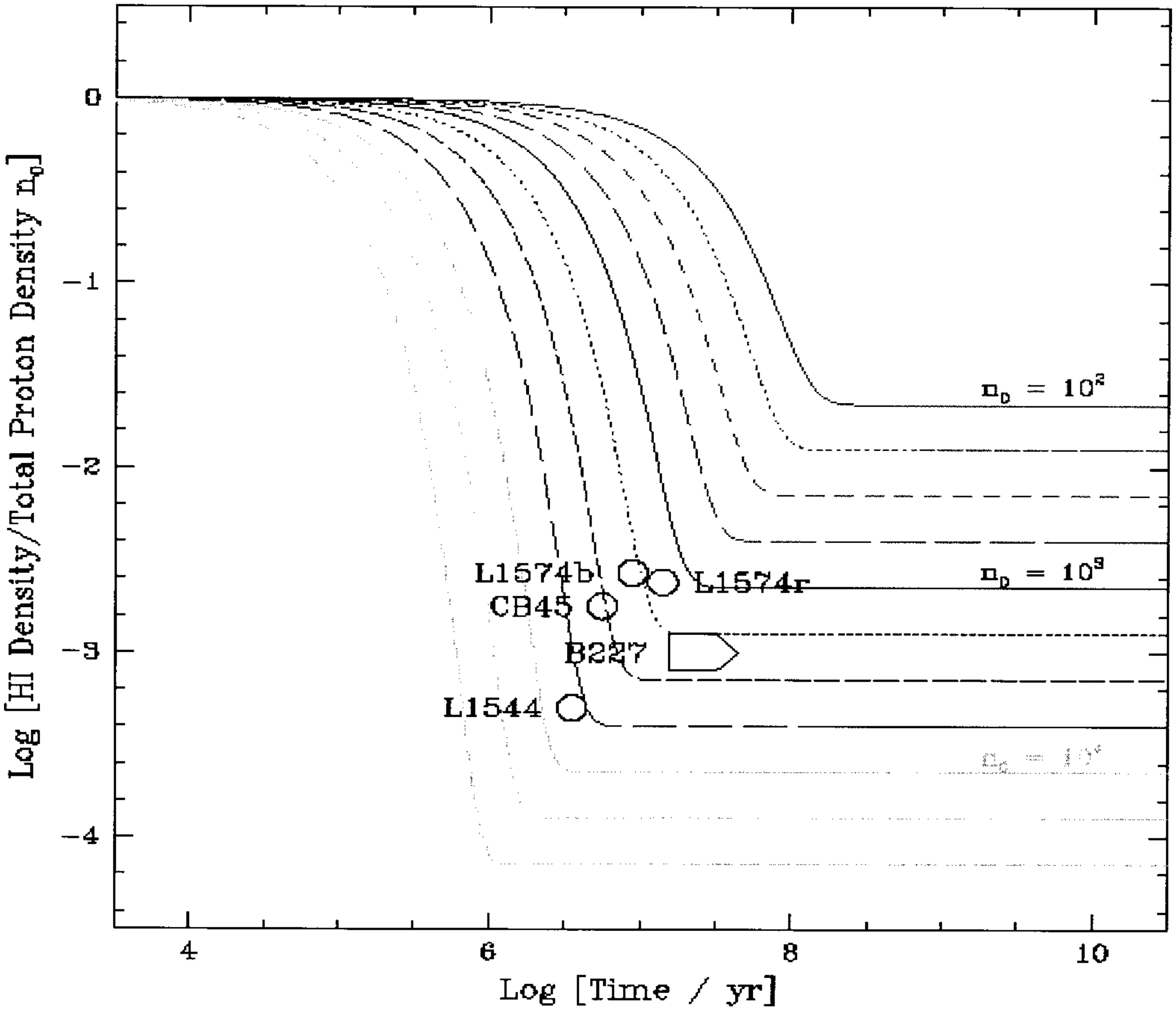
Time scale for conversion for high density gas which will become predominantly molecular

$T = 1/2Fn_0 = 2.6 \times 10^9\ yr / n_0$

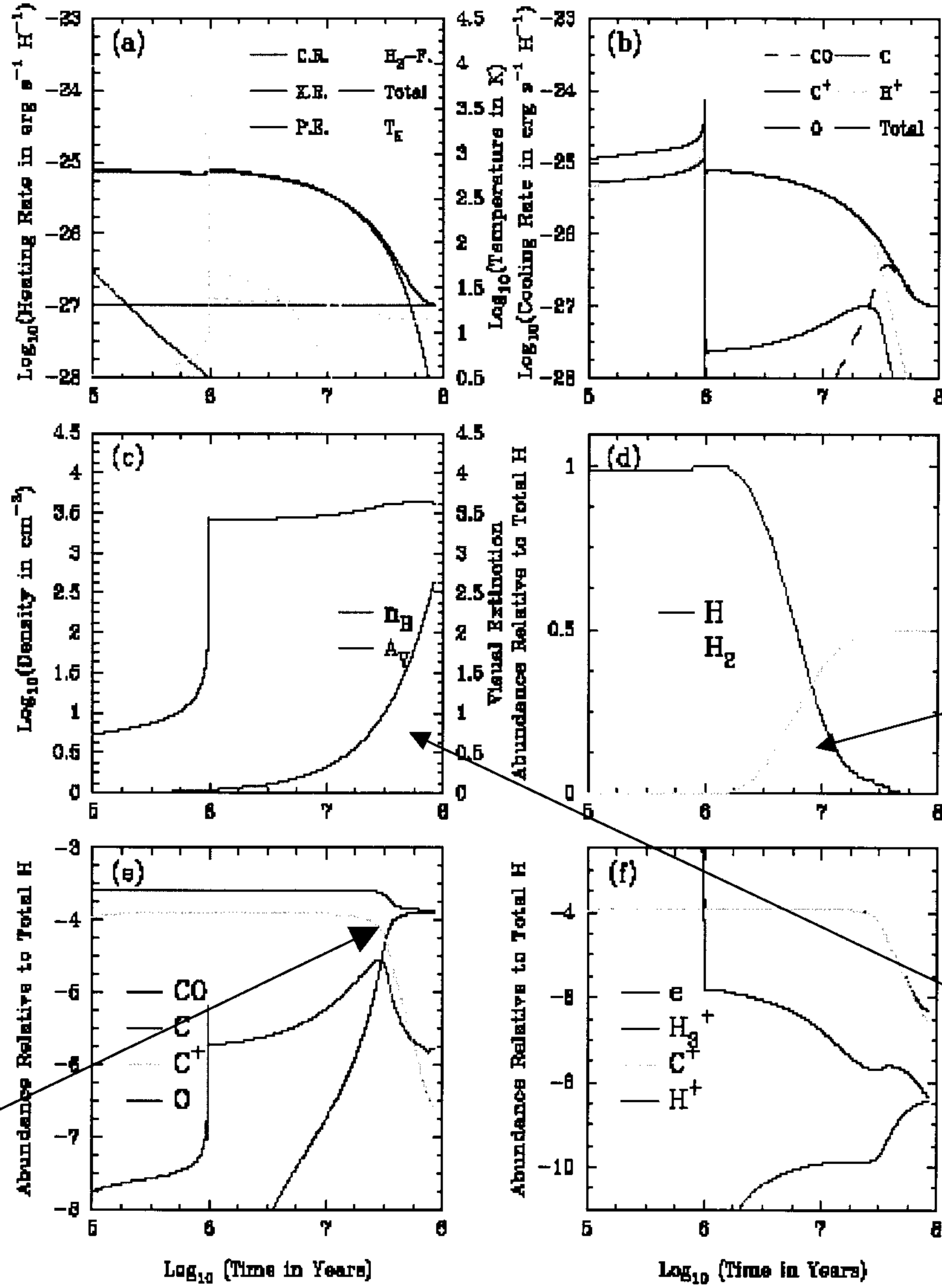
$= 10^6\ yr$ at densities derived for clouds mapped, using ^{13}CO & standard $X(^{13}CO)$ to determine column densities

Low HI fractional abundance => cloud "age" must be minimum of several times T

Time Dependence of HI Fractional Abundance



What do observations of HINSA tell us about molecular clouds and star formation?



HI ~ H_2 after 10^7 yr

$A_v = 1$ after 3×10^7 yr

Large-scale formation of molecular cloud from atomic gas by 20 km/s shock wave
$n_0 = 1$ cm^{-3} T=10^3 K

[Bergin et al. 2004]

CO dominates After 3×10^7 yr

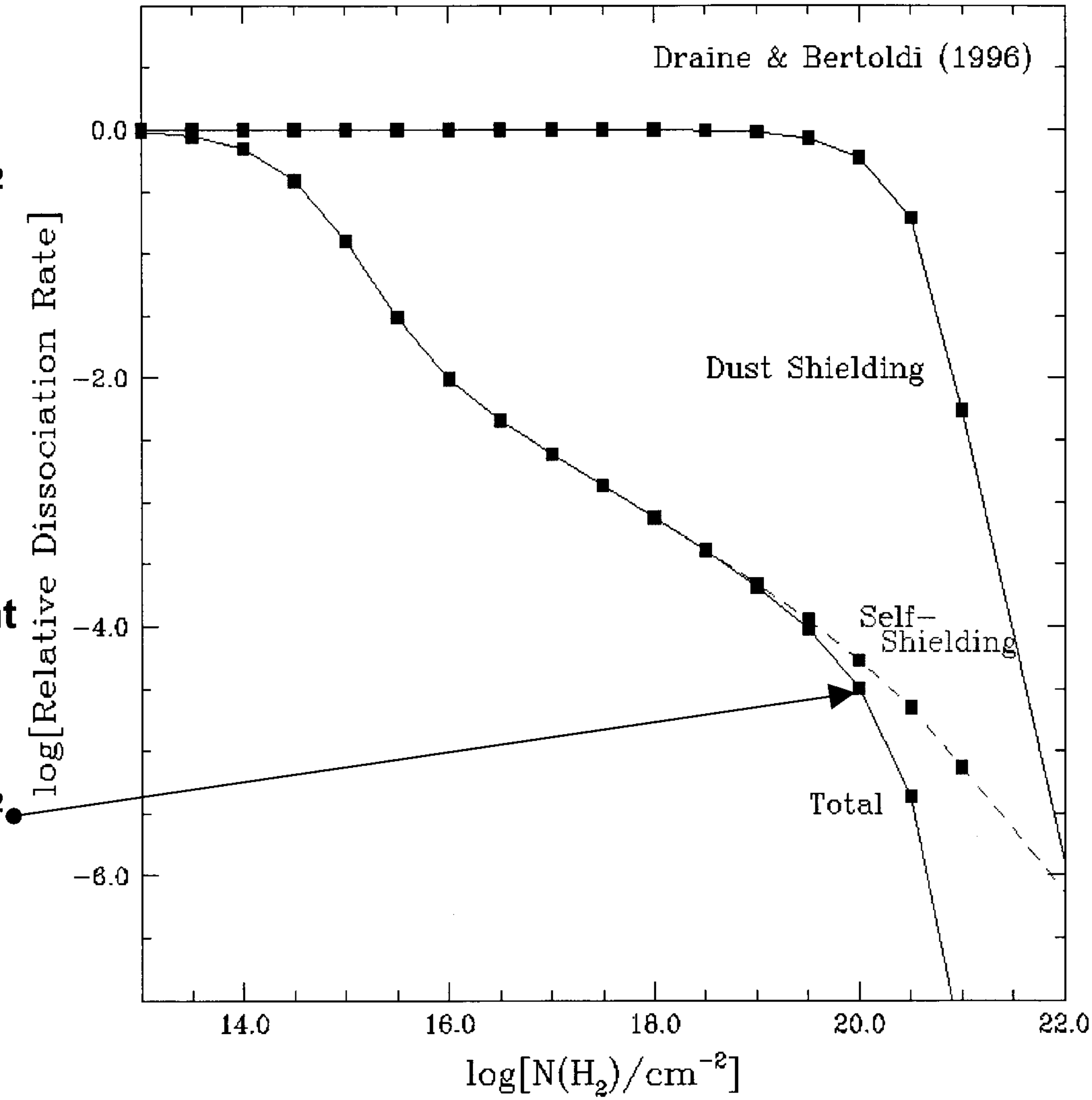
CO and H_2 Formation

- While self-shielding is more effective for H_2 than for CO, the very low fractional abundances of HI which we see require that the H_2 photodissociation rate be drastically reduced relative to that in ISRF
- Even then, it requires significant time to convert hydrogen from atomic to molecular form

Getting Rid of the Atomic Hydrogen

- To get $n(H) \sim n(H_2)$ requires $N_0 \sim 10^{20}$ cm^{-2} ($A_V \sim 0.1$ mag)
- But, to get $n(H)/n(H_2) \sim 0.001$ as observed requires that photodissociation rate must be $<$ cosmic ray dissociation rate since our results are close to steady-state abundances considering only CR destruction of H_2
- What does this say about min. column density?

Reduction in H_2 dissociation rate from dust and self-shielding



Self-shielding of H_2 is important but dust shielding is significant for $N(H_2) > 10^{20}$ cm^{-2}

The HI to H_2 Transition and Molecular Cloud Formation

Cosmic ray dissociation rate:

$D = 2.5\times10^{-17}\ s^{-1}$

Photodissociation rate in unshielded ISRF:

$Z = 3.2\times10^{-11}\ s^{-1}$

We require minimum attenuation of 10^6 to get $Z < D$

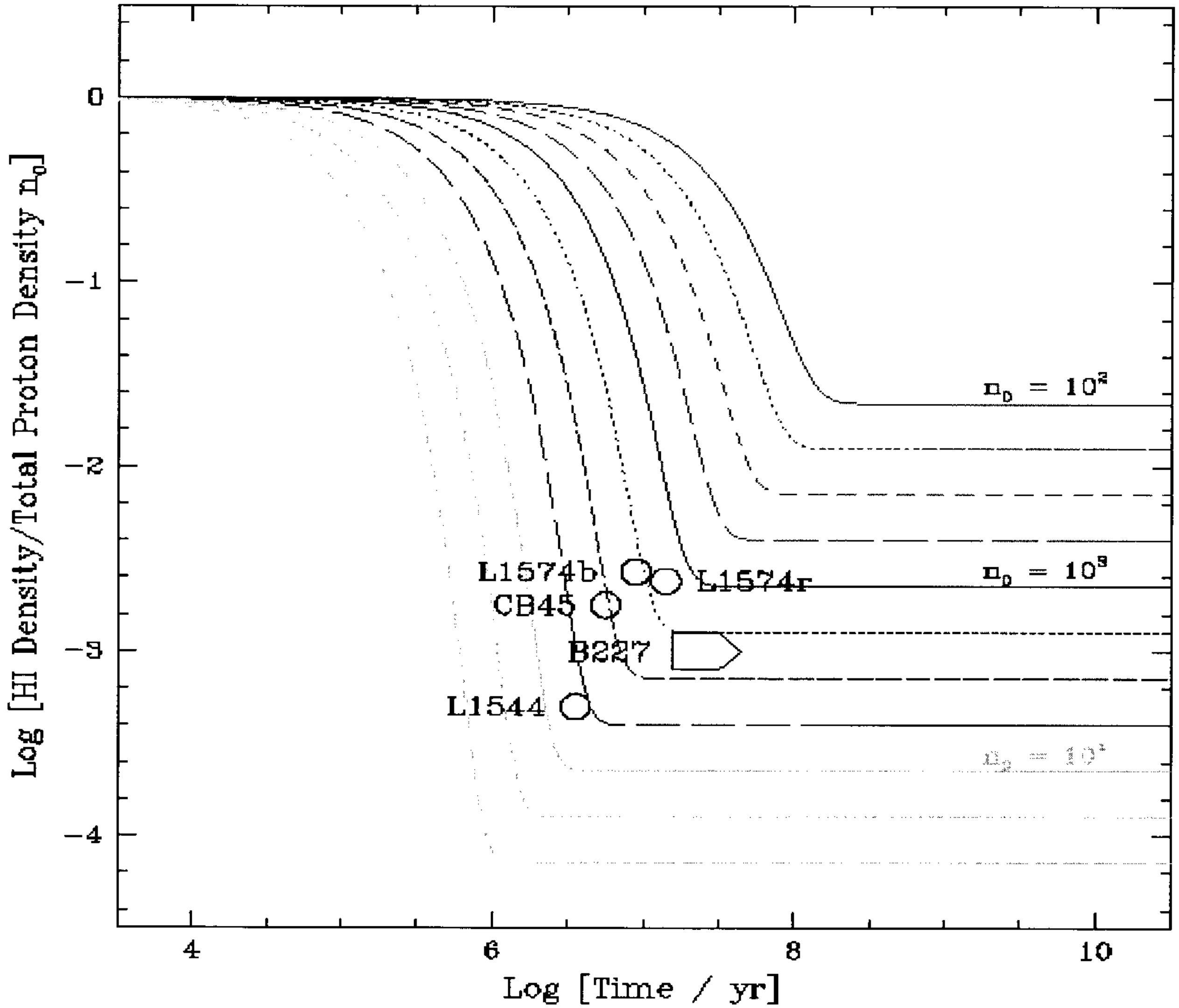
This occurs for $N \sim 10^{21}\ cm^{-2}$ or $Av \sim 1$ mag; the same required to get a "CO cloud"

The HI to H_2 Transition and Molecular Cloud Formation

- Buildup of column density of 10^{21} cm^{-2} requires time ~ $3x10^7$ yr in Bergin et al. model
- This would then mark "t=0" in our calculation
- Total "age" of observed clouds in context of this model ~ 10^8 yr
- This could possibly be reduced if instabilities, fragmentation, and self-gravity increase the density

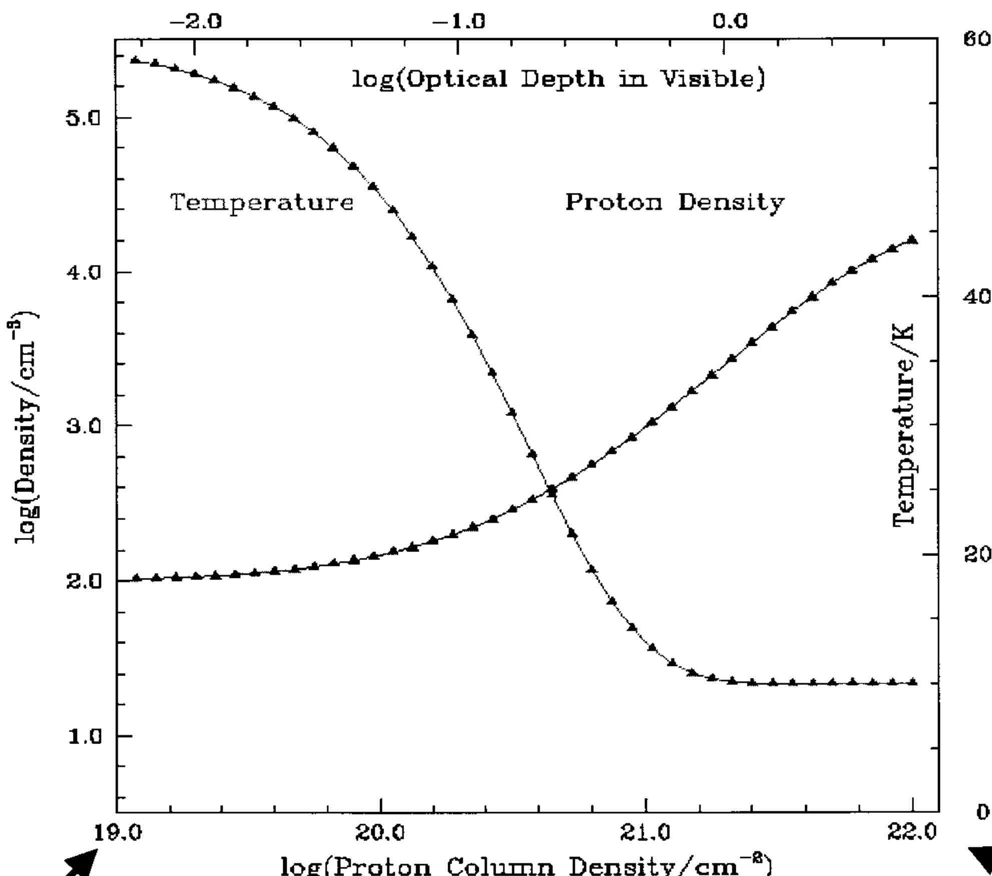
  Note, however, that our measured densities ~ those in postshock gas of Bergin et al.

Time Dependence of HI Fractional Abundance



Evolution following moment when visual extinction becomes > 1 mag

Model Cloud: Initial Conditions



Initially atomic -

$N_0 = 1x10^{22}$; Av = 5

$n_0 = 2x10^4$ in core +

r^{-2} outside (slab)

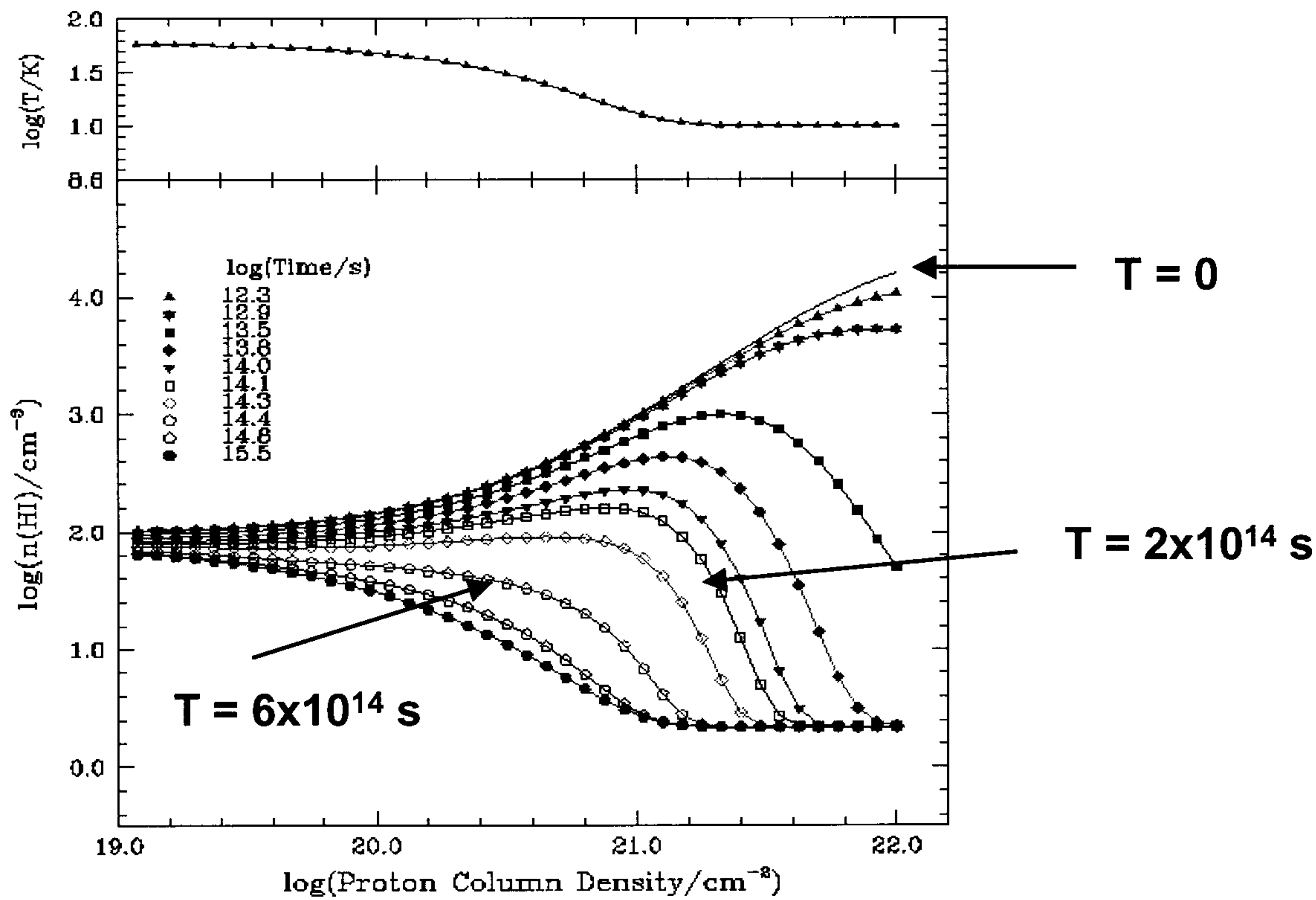
Hot-edged due to heating by ISRF

Outside

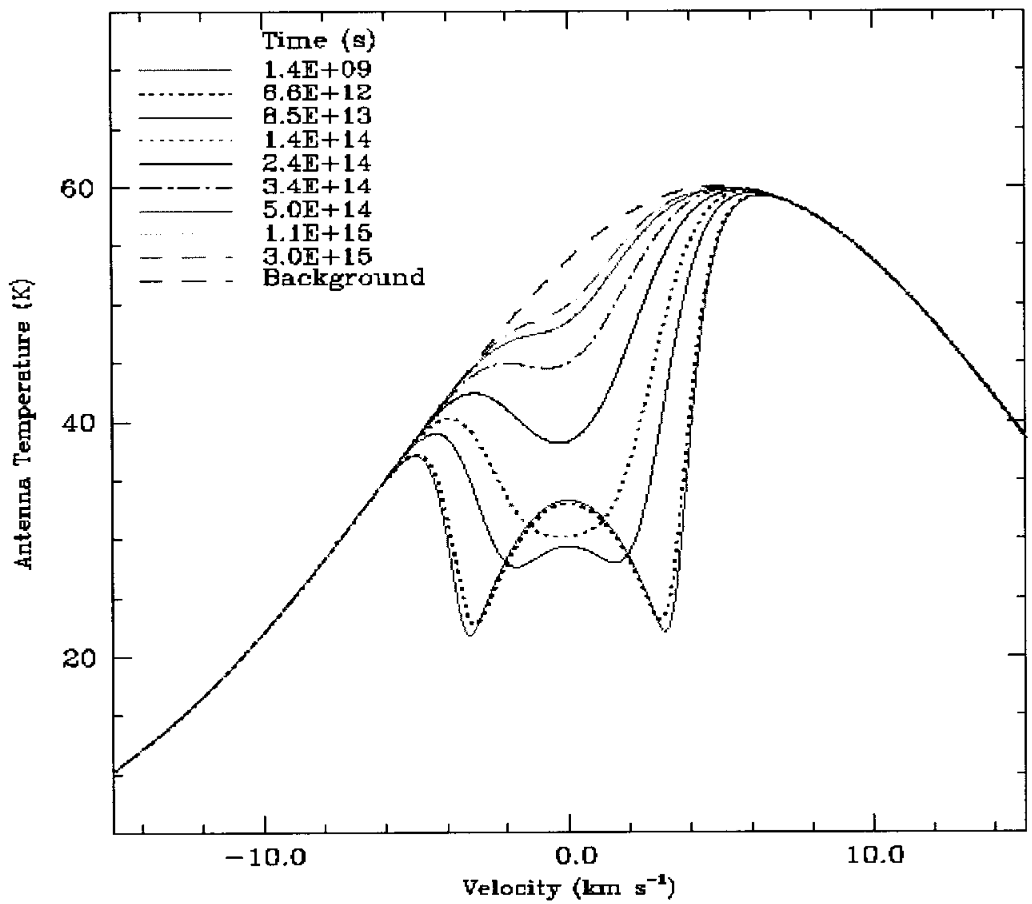
Center

Time Evolution of the Cloud

A wave of HI destruction and H_2 formation sweeps out from the center of the cloud



HI Absorption Spectra Indicate $T > 10^{15}$ s to reproduce observations



Conclusions from Observations of HI Narrow Self Absorption (HINSA)

Local molecular clouds have HI well-mixed with molecular constituents

This HI is cold, quiescent, and must be well-shielded from the UV radiation field

The density and fractional abundance (wrt H_2) of the cold HI are close to steady state values

The time required to convert these starless clouds from purely HI initial state to observed present composition is a few to ten million years

This timescale is a lower limit – if dense clouds being swept up from lower density regions by shocks, the time to accumulate material to get $A_V \sim 1$ and provide required shielding may be comparable or longer