The Effects of Density Waves on the ISM in Spiral Galaxies:

An observer's view

–

Some personal recollections, recent results, and thoughts for future work

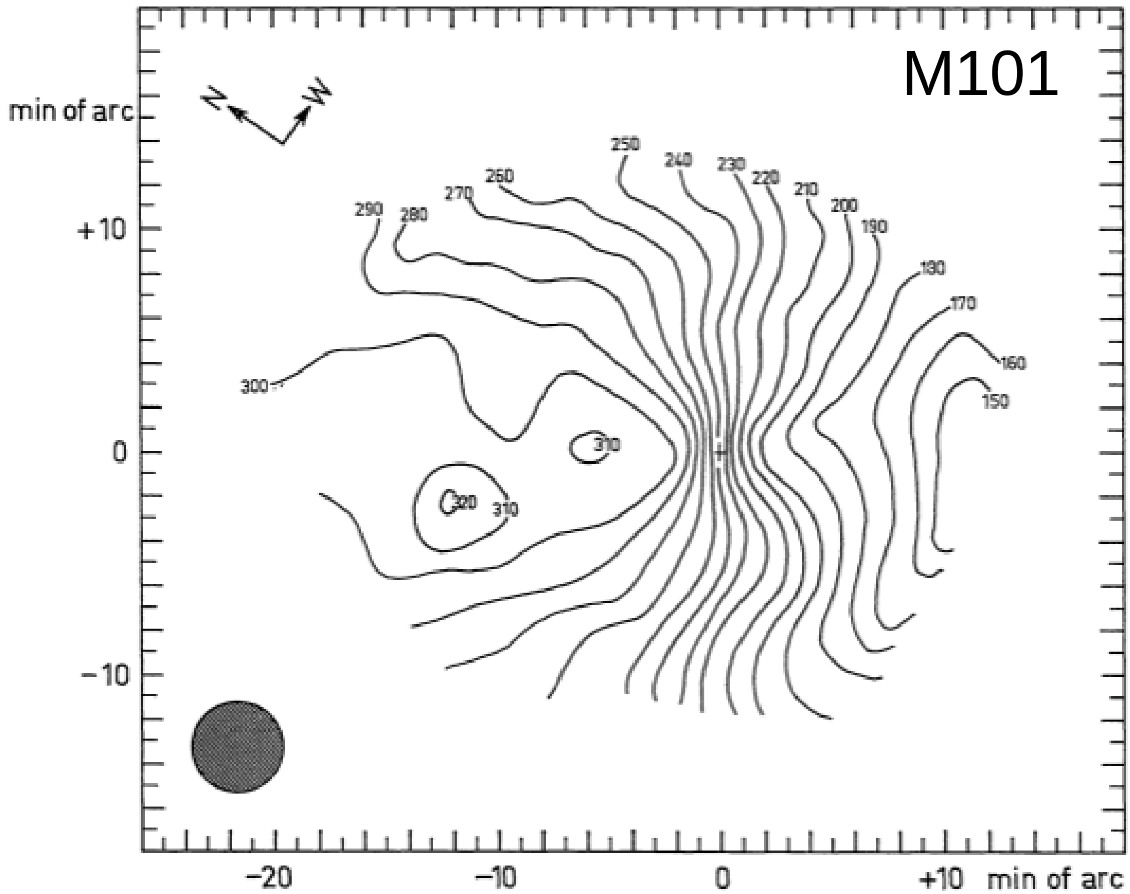
Ron Allen

Space Telescope Science Institute

Outline of this talk

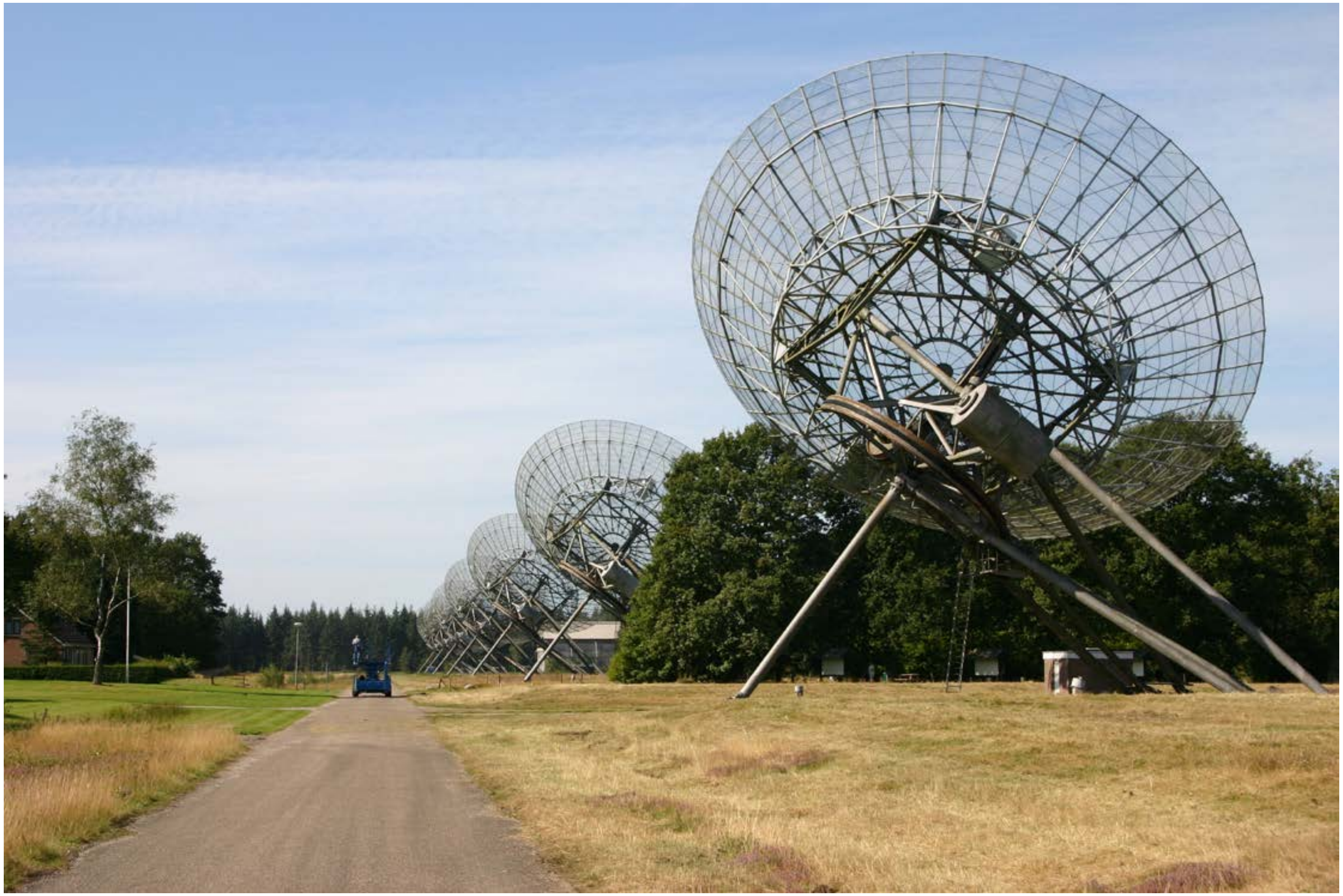
- Some history:
  - 1969: my introduction to Density Waves
  - 1970: the WSRT 80-channel receiver project
  - June 1971: discussion with CC Lin, Frank Shu, etc.
  - Winter 1971-72: first WSRT observations of M101
  - Summer 1973 (???): Frank (and Helen) visit in Groningen
  - 1975-1980: the iconic picture of HI motions in M81
  - 1985-2005: trouble in paradise …
  - 2010+: some recent results ...
  - thoughts on future directions.

My introduction to Density Waves



Rogstad & Shostak 1971

The Westerbork Synthesis Radio Telescope



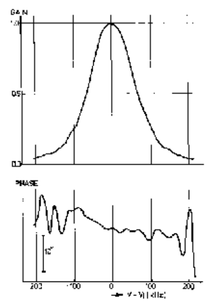
The WSRT 80-channel receiver project

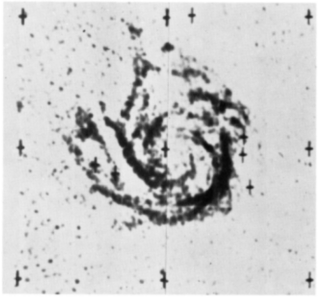
252

the weighting (or grading) function H(τ) used in the temporal Fourier transform, i.e.

frequencies of the phase rotators in each of the 28 local oscillator lines in such a way that the fringes for the centre of the observed field are demodulated. As the residual fringes have a low frequency

The 80-channel Analog Line Backend

0.6 x WSRT + 

= 

The first WSRT spectrometer 1971-1977

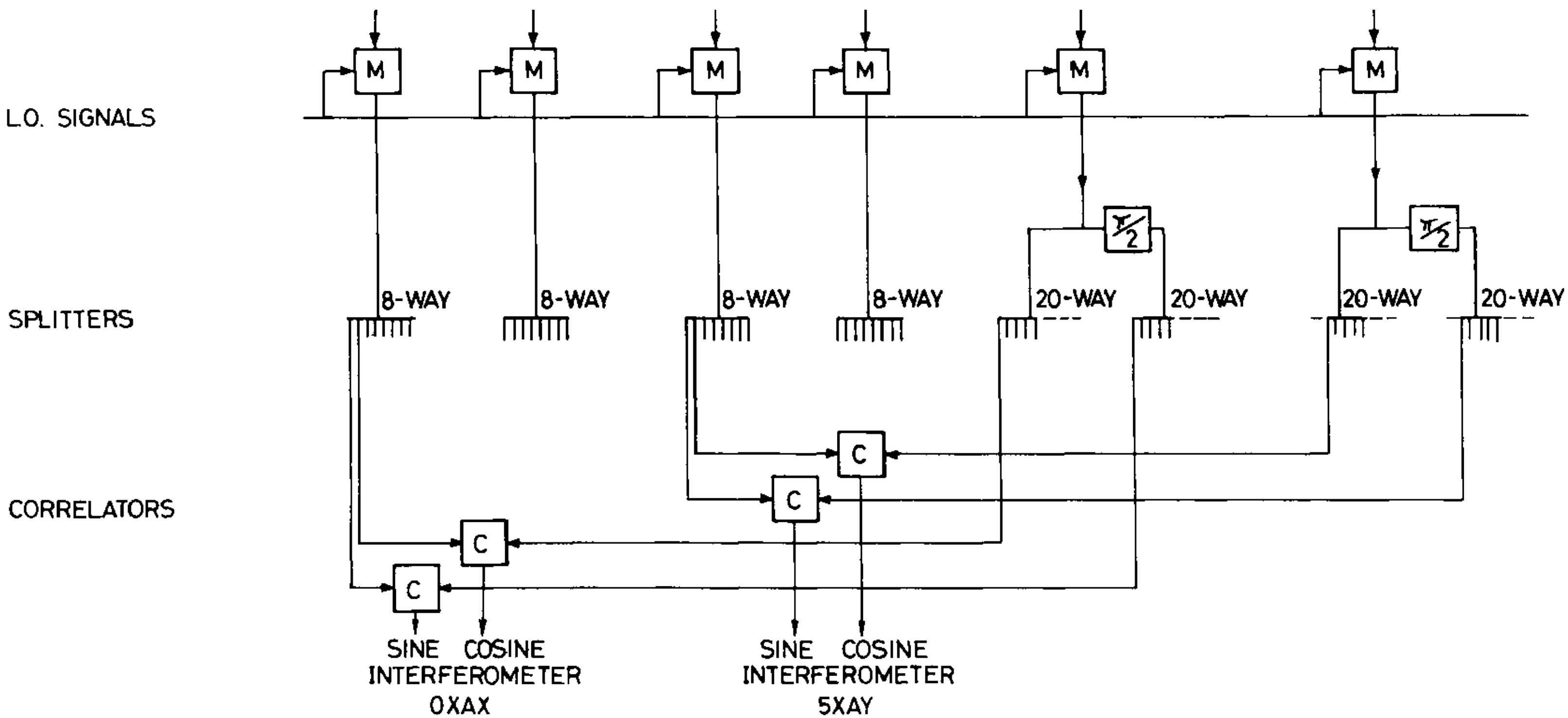
Overall project chronology

- 1970 – Initial scientific motivation: D. Rogstad /OVRO/M101/HI
- Dec 1970 – Informal acceptance by SRZM *
- 1971 – the year it all happened …
  - Formal approval by SRZM (I was in Cambridge Jan-Feb 1971 …)
  - Hardware design, construction, testing …
  - RJA visit to MIT (C.C. Lin, Frank Shu, & colleagues) to talk about DWT
  - Observing program negotiations Leiden (Oort) ⇔ Groningen (HvW) **
- Dec. 1971 – Jan. 1972: First full-system observations
- 1972 – 1977 routine operation (6 yrs)
  - shared line/continuum, 21 & 6 cm
- Fall 1977 - Decommissioned in favor of DLB

Project time line 1970-71

- Scientific goal: HI distributions + motions in galaxies
- Design studies (1970): RJA, Rogstad, van Woerden, Schwarz
- Technical feasibility, final general design (Dec 70):
  - A. Muller, E. Raimond, J. Hamaker, K. Wellington, RJA
  - Install different splitters and new filters in the 30 MHz IF
    - Turn 20 interferometers X 4 polarizations (existing cont. system) into 10 interferometers X 8 frequencies
  - Install new 120K paramps in A, B
    - $T_{sys} \approx$ 170K (with old 240K paramps in telescopes 0-9)
  - Software modifications - v. Someren-Greve, Brouw
- *Construction, test, commissioning (Jan - Nov 71)*

How it was done – before:



ı components of the continuum polarization receiver as discussed in Section 2. Only 2 out of the 80 pairs of correlato
g with 2 of the 10 fixed reflectors (0, 1 ... 9) and one of the two moving ones (A, B)

Allen, Hamaker, & Wellington 1974

How it was done – after:

Ronald J. Allen *et al.*

ıannel Spectrometer Design

ſodifications

bork system has been described by Baars
 and further papers on various features of
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We confine ourselves to a brief discussion oſ
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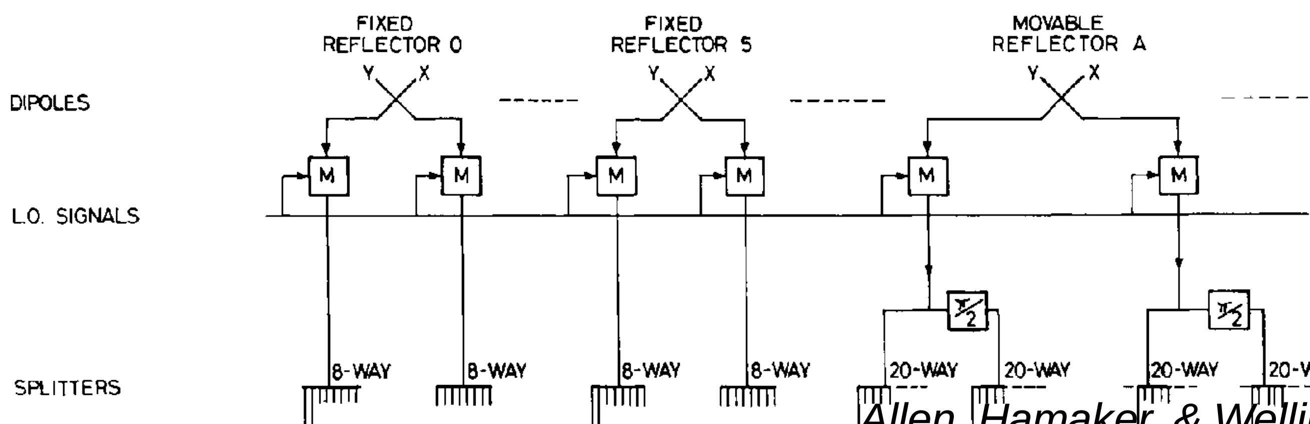
continuum emission from cosmic radio sourcɛ
principle behind the modifications is to tal



Allen, Hamaker, & Wellington 1974

We traded many expensive parts …

Ronald J. Allen *et al.*

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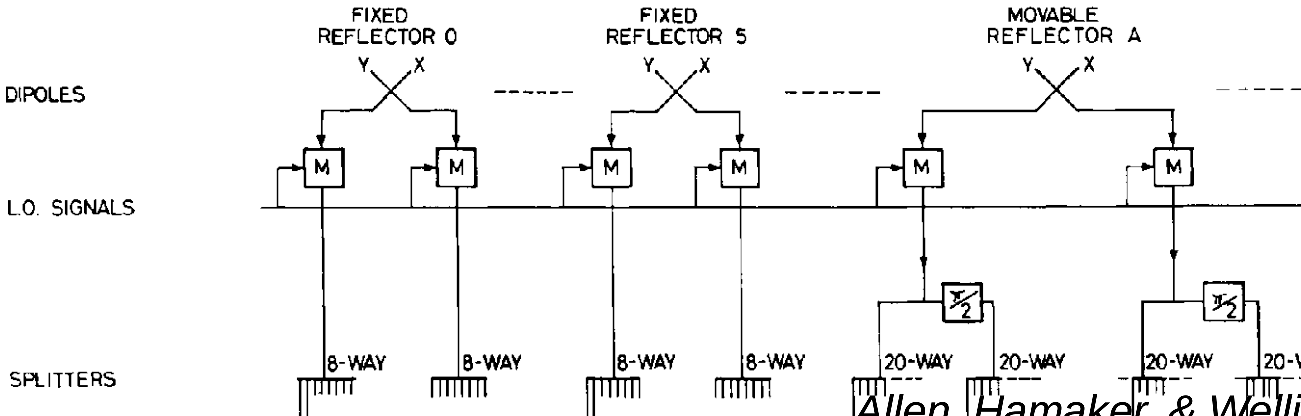
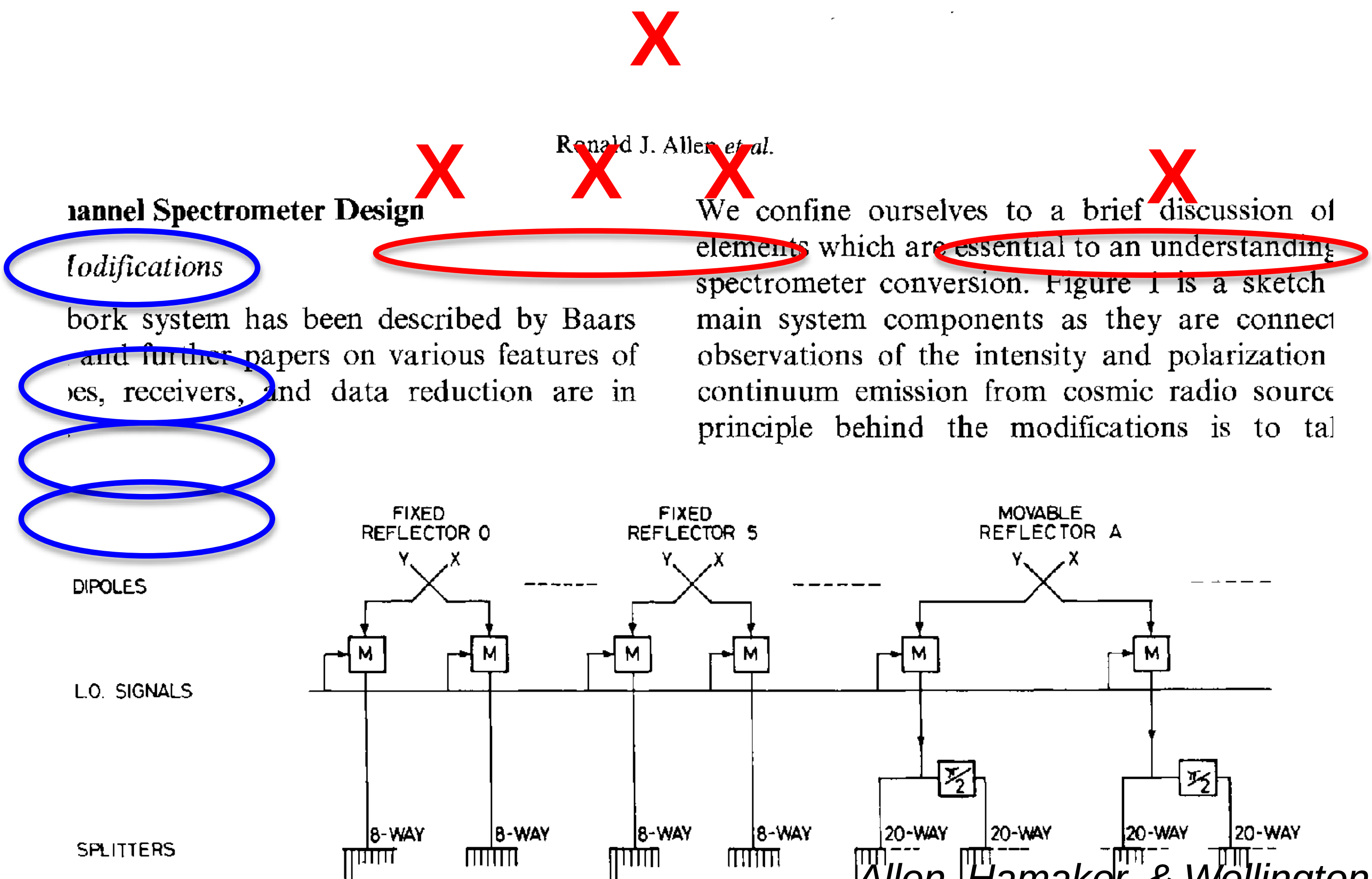


Allen, Hamaker, & Wellington 1974

… for some cheap electronics …



Allen, Hamaker, & Wellington 1974

… and a new paramp.

Ronald J. Allen *et al.*

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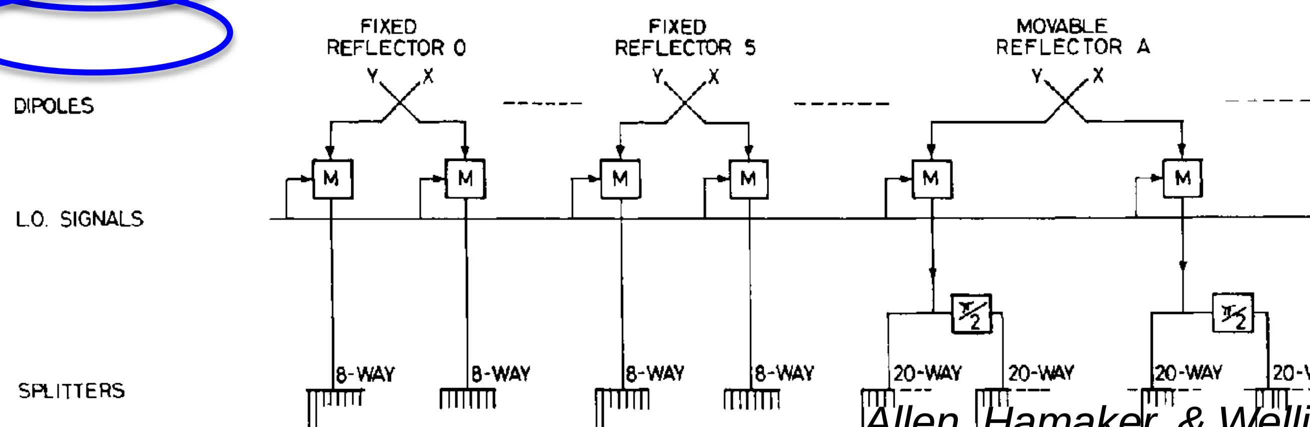

Allen, Hamaker, & Wellington 1974

(… and it all had to work, or
I would have been looking for another job …)

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(… after all, there I was, a lowly postdoc …)

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(… proposing to take this beautiful new instrument which had been painstakingly designed and built at great cost, and do something special with it …)

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(… after all, there I was, a lowly postdoc …)

(… proposing to take this beautiful new instrument which had been painstakingly designed and built at great cost, and do something special with it …)

(… ***by leaving 5 of the 12 telescopes idle!***)

A pilgrimage … June 1971

Discussion at MIT - 9 June 1971

- Introducing the main players:
  - The (clueless) visitor, the (not-yet-famous) student, and the (already-famous) Professor.
- Which galaxies to do first?
- How much resolution is needed?
- What constitutes a definitive test of the theory?

1972: An early result with the WSRT

continuum radiation measured in 4 line-free channels, and summation of the line radiation in the remaining 12 channels gave profile integrals, and (assuming small optical depth) column densities N_H. Figure 3 is a contour map showing the distribution of N_H. The noise error on N_H is $(1-2) \times 10^{20}$ atom cm^{-2}; the outer contour in Fig. 3 (4×10^{20} cm^{-2}) has been slightly smoothed.

The map in Fig. 3 has a few imperfections. The lack of baselines shorter than 36 meters attenuates larger-scale structures (for instance, by a factor ≈ 2 for structures of 10′ size), and depresses the zero level of the map. A further underestimate of N_H is due to the fact that, in order to minimize the noise in the profile integrations, we have neglected channels with intensities below 2σ, i.e. $T_b < 3$ K; this error may become serious for wide, faint profiles. Finally, the brightness temperatures measured have not been corrected for attenuation in the primary beam (halfwidth 0°.6); consequently, the N_H scale increases systematically away from the map centre. However, the values for H I masses in individual concentrations (Section 3) have indeed been corrected for this attenuation.

The imperfections mentioned do not seriously affect the smaller-scale structure in the system, which is the subject of this paper.

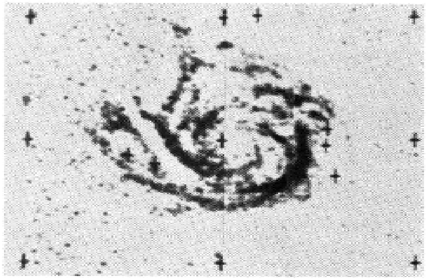


Fig. 1. Radiograph showing distribution of column density of neutral hydrogen in M 101. Large-scale (> 10′) components in the distribution are not recorded. North is at top, west at right in all figures. The radiograph contains crosses at 9 fiducial points as well as the positions of 6 stars. The mottled appearance of the background in the radiograph arises from noise and the size of the smallest spots is about that of the telescope beam

3. Results and Discussion

a) The Distribution of Neutral Hydrogen

Figure 1 is a "radiograph" of the distribution of N_H, the column density of neutral hydrogen. This photographic representation of the profile integrals displayed on an oscilloscope screen (cf. Ekers *et al.*, 1973), compared with a blue photograph (Fig. 2) taken from Arp's (1966) *Atlas of Peculiar Galaxies*, clearly shows the similarity of the distributions of H I and of blue stars and ionized hydrogen. Note that even the weak outer H I arms in the SE quadrant do have optical counterparts visible in deep exposures.

Figure 3, presenting an overlay of the N_H contours on the blue photograph, emphasizes this similarity: except for radii $< 2-3'$, the H I ridges follow – or, indeed, coincide with – the optical arms to within the 0′.5 resolution, out to almost 15′ from the centre. This result refutes some of the statements recently made by Piddington (1973). The close correspondence includes

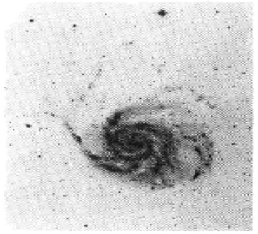


Fig. 2. Blue photograph of M 101, from Arp's *Atlas of Peculiar Galaxies*. Scale same as Fig. 1

Fig. 3. Overlay of contours of hydrogen column density (N_H) on the blue photograph. Contour levels are, approximately: $(4, 12, 20, 28) \times 10^{20}$ atoms cm^{-2}. However, for reasons discussed in the text, the N_H scale increases somewhat away from the centre of the galaxy and the zero level of the N_H contours is uncertain. The angular scale is shown at lower left (1 arc min = 2 kpc), the synthesized beam in the lower right corner. Note the close, detailed correspondence of optical and radio features. The brightest H II regions, indicated by their NGC numbers, have all been detected in the continuum. The cross in the nucleus of the galaxy corresponds to: (1) an optical H II region, (2) a weak associated radio source, and (3) the centre of the galaxy as defined by the light distribution on blue photographs. The other crosses are fiducial marks in the hydrogen map corresponding to positions of stars. The 3 historical supernovae in M 101 (SN 1909a at 12′NW, SN 1951 at 6′E, and SN 1970g at 6′S) are indicated by white dots

Allen, Goss, & Van Woerden 1973

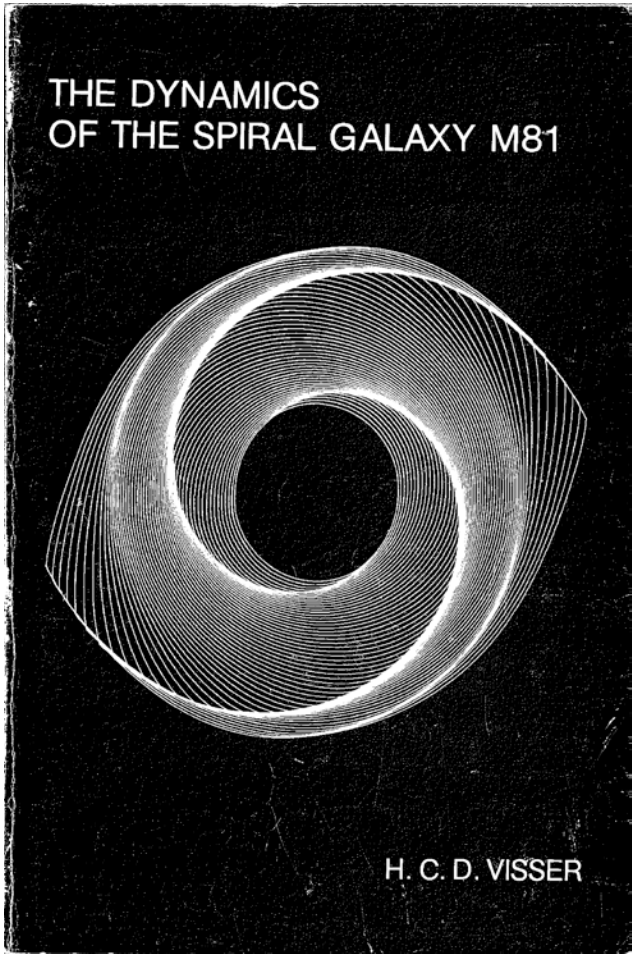
Scientific productivity - I

- 43 Refereed papers (1973-1986)
- 21 nearby galaxies HI emission mapping:
  - Large galaxies M31, M81, M101
  - NGC 4258, 4151, 4736, 5475, 5477, 4631, 4656, 4038/39, 891, 3077, 5383, 4490/85, 2685, 5033, 3198, 5055, 2841, 7331
- 6 PhD Theses (in whole or in part):
  - A.H. Rots, G.D. van Albada, A. Bosma, J.M. van der Hulst, B.M.H.R. Wevers, H.C.D. Visser

Scientific productivity - II

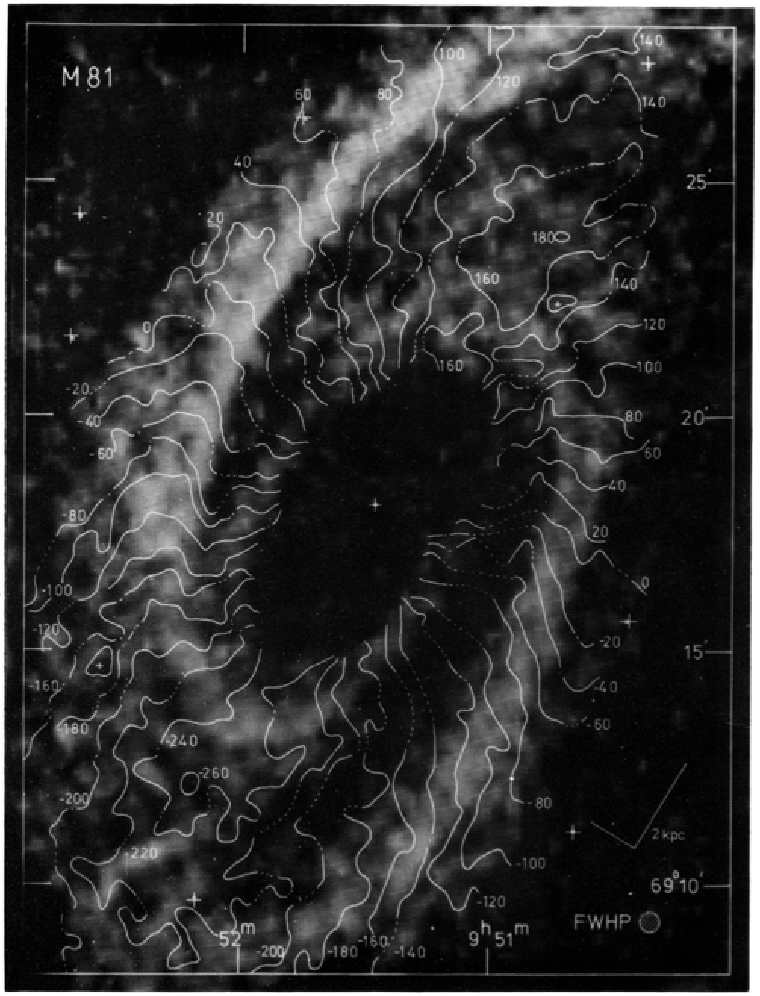
- 6 H109α recom line emission mapping:
  - DR21, W3, M82, W49A, W51A, K3-50
- 4 dwarf galaxies HI emission mapping:
  - DDO125, HoI, IIZw70, IIZw71
- 3 galaxy groups HI emission mapping:
  - Stephan's Quintet, NGC 2805-2814-2820-Mark108, NGC6503/1749+70.1
- 2 Galactic HI absorption mapping:
  - 3C10, 3C58

Results: Density Waves in M81

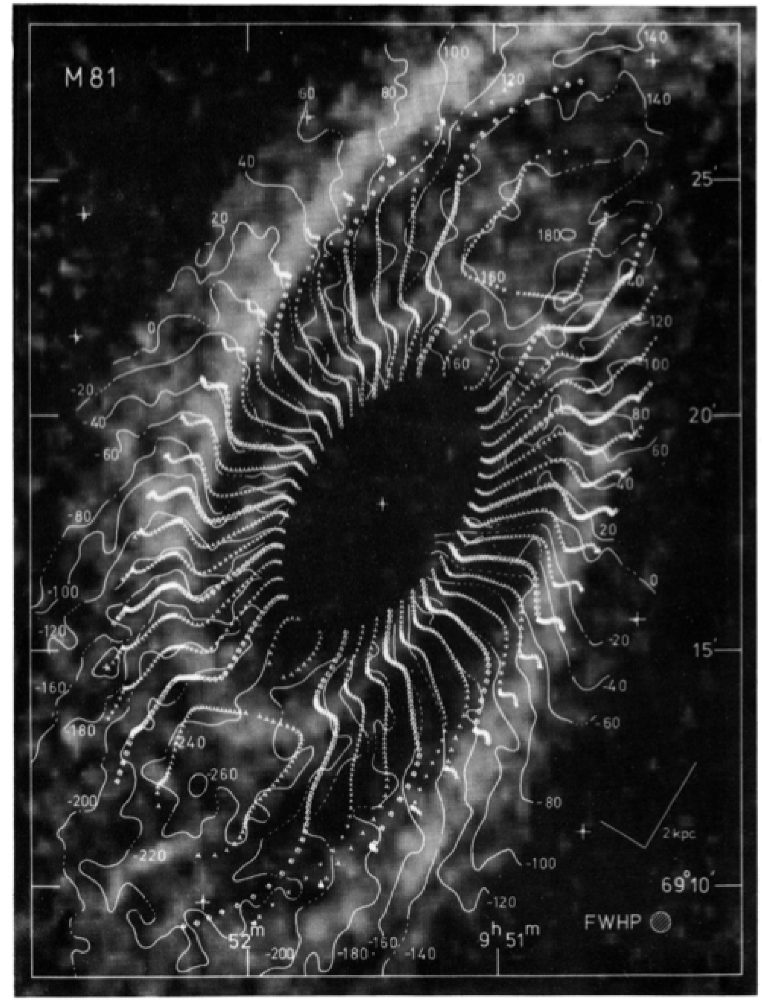


Visser PhD Thesis1978

Results on M81 ... velocity field

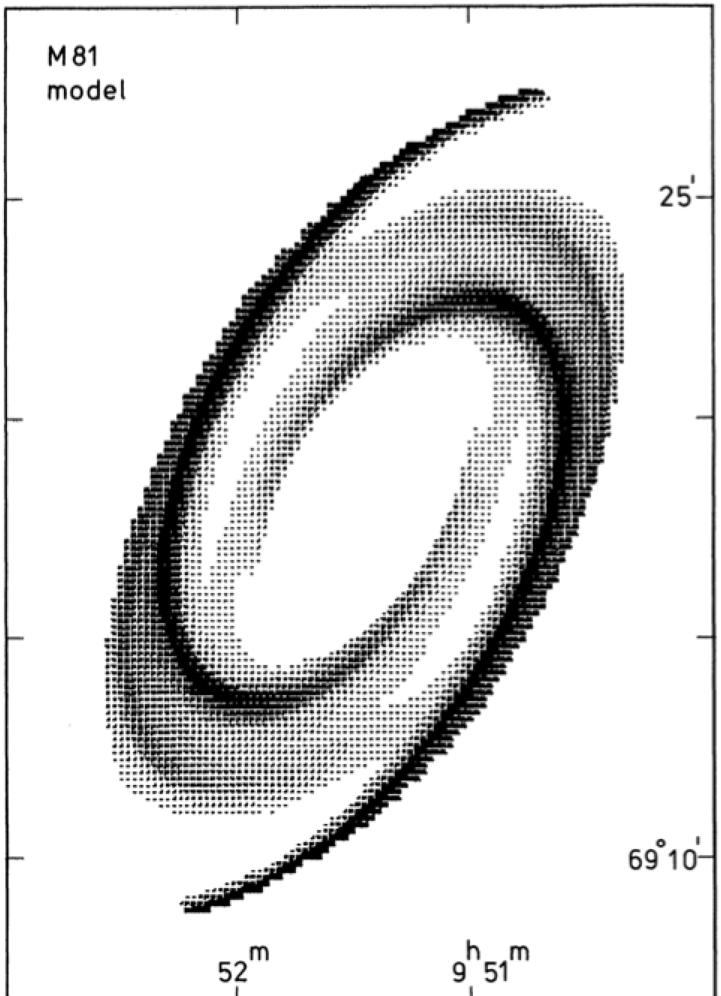


WSRT Observations: Rots (1974)

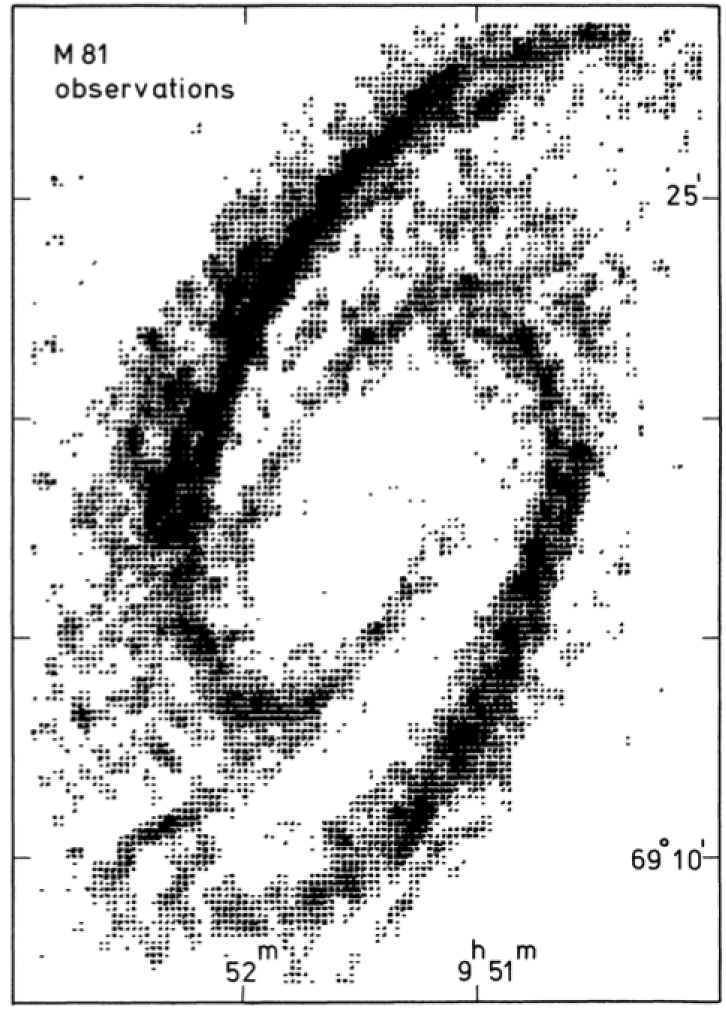


Theory + observations: Visser 1980

Results on M81 … gas distribution



Density Wave Theory: Visser 1980b



WSRT HI: Rots & Shane 1975

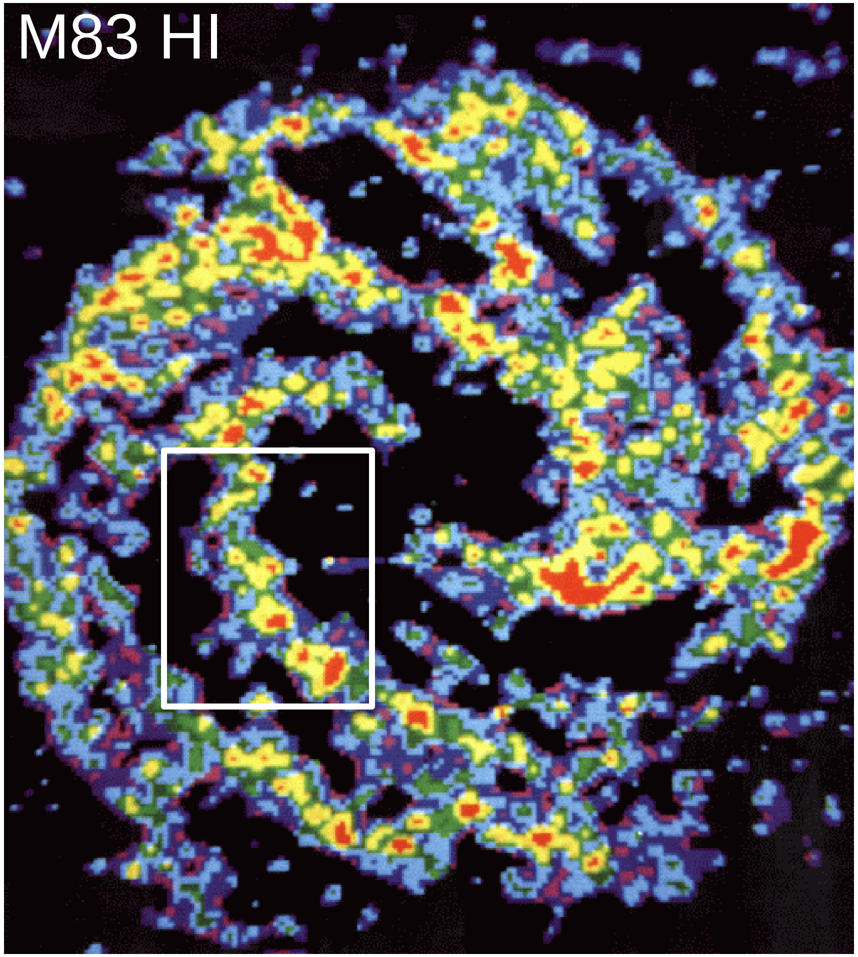
By 1980 we had surely *killed* this problem ...

- Visser's thesis summarized our accomplishments, but our satisfaction was short-lived ...
- In the early 1980's, the VLA began to observe HI in galaxies at even higher resolution, and was able to operate well in the southern hemisphere.
- The sample was extended to a larger number and to a wider variety of nearby galaxies.
- Soon there was ...


ernst
LUBITSCH'S
TROUBLE IN PARADISE
MIRIAM HOPKINS · KAY FRANCIS · HERBERT MARSHALL
CHARLIE RUGGLES and EDWARD EVERETT HORTON
A Paramount Picture

1932

The VLA view of HI in M83



- A nice picture, but something was not quite right …
  - It agreed with the observation that more HI was associated with more young stars, but …
  - The detailed morphology of the arms did not fit the DWT/TASS model, where the 21-cm HI in spiral arms is supposed to trace the *precursor gas* from which massive stars are made.

Some background - the “TASS” picture ...

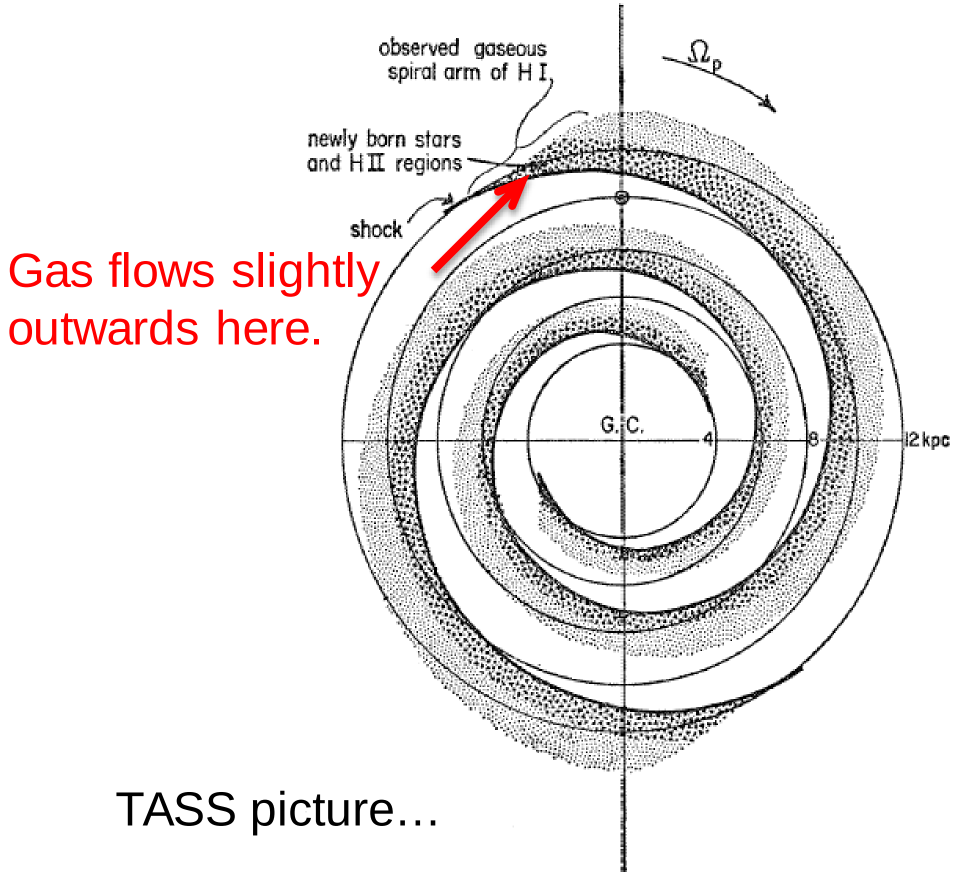


FIG. 7.—Spiral pattern in the Galaxy: the observable picture. The location of the shock and the sharp H I peak and the possible locations of the regions of newly born luminous stars and the H II regions lie on the inner side of the observable gaseous spiral arm of H I (of trailing type).

W.W. Roberts 1969

... did not fit new VLA data ...

- The dust lane in the TASS picture traces the maximum gas surface density near the shock.
- But the ridge of HI in the inner eastern arm of M83 *did not line up with the dust lane*.
- Instead, the HI ridge appeared *downstream* from the dust lane (in a DWT-streaming sense).

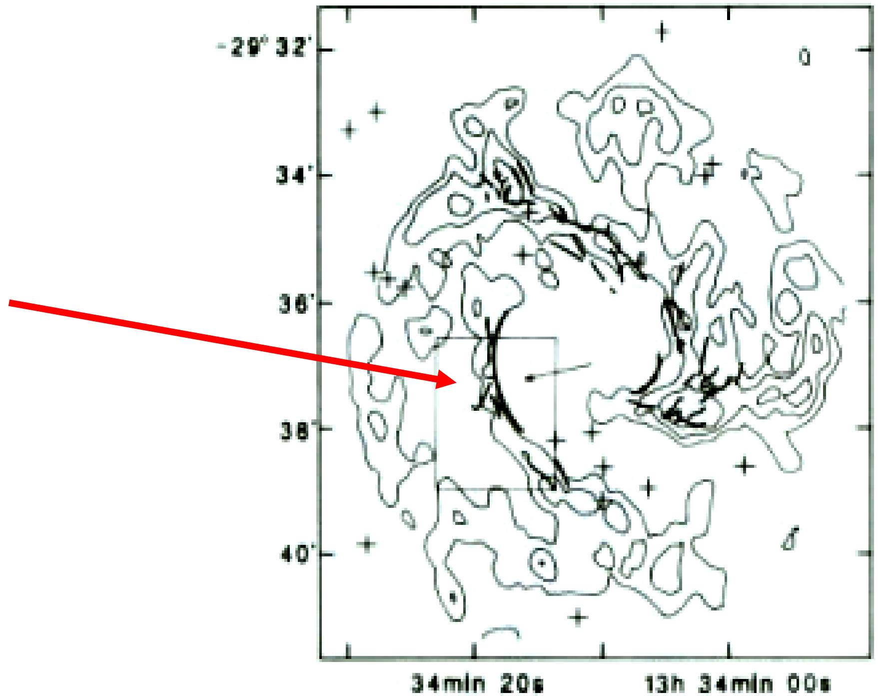


Fig. 1 The distribution of atomic hydrogen and dust lanes in M83. Contours are taken from VLA-H I synthesis observations at 25 arc s resolution. The dust lanes have been drawn from inspection of an optical photograph. The crosses refer to a set of secondary standard stars. The arrow indicates the inner eastern arm; the frame drawn corresponds approximately with the frames of Fig. 2.

Allen, Atherton, & Tilanus 1986

HI is *anticorrelated* with dust and with Hβ

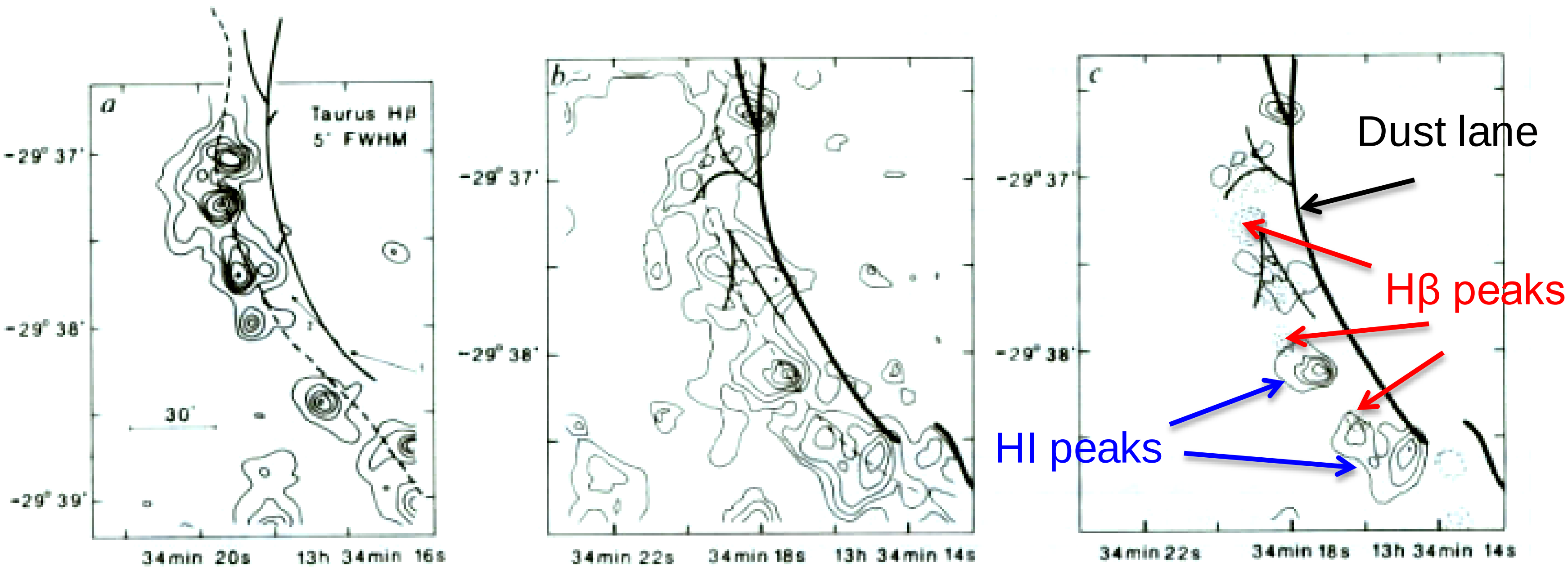


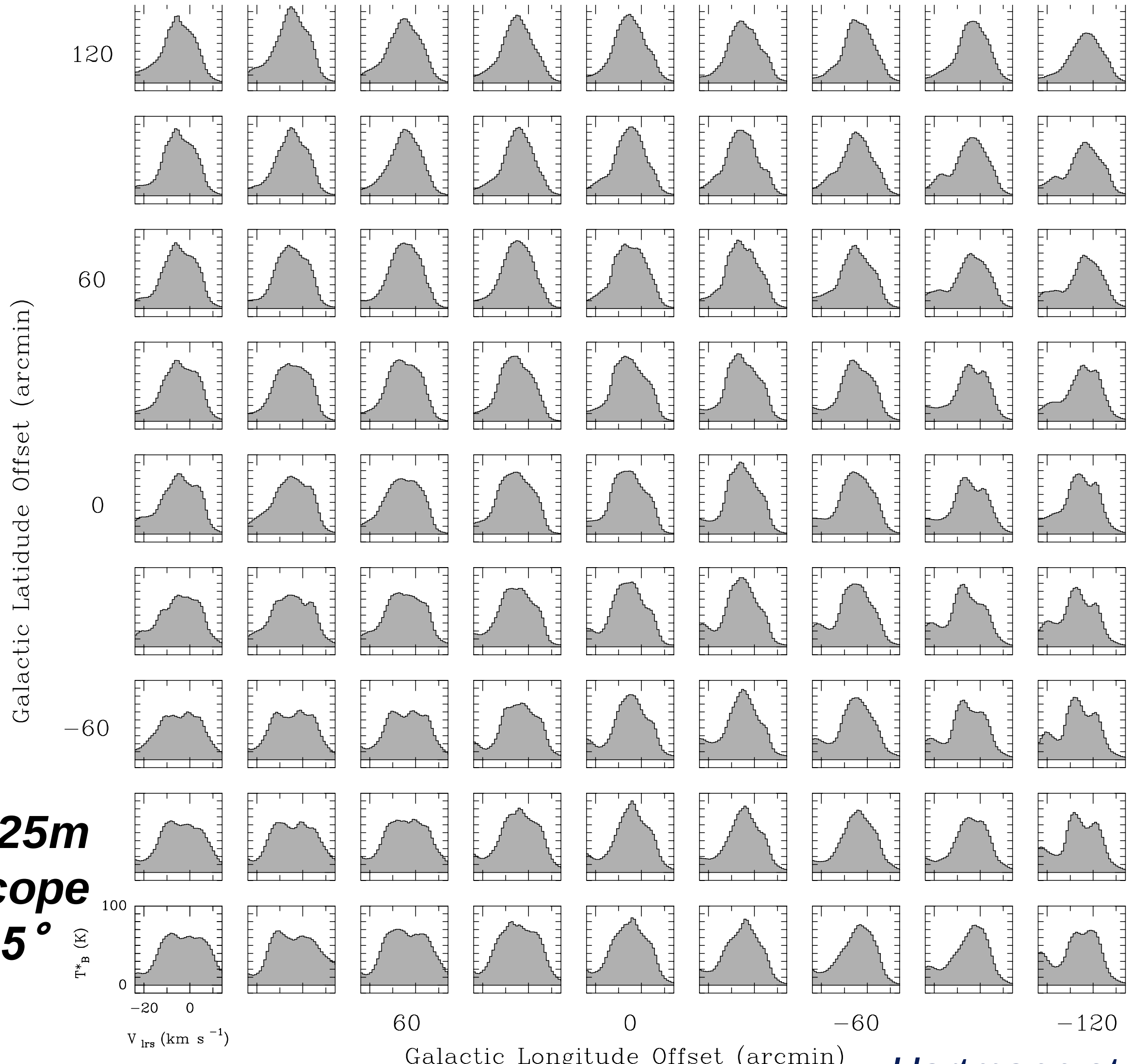
Fig. 2 *a*, The distribution of dust (thick solid line), H β emission (contours, 5 arc s resolution), and the ridge line of the H I from the contours in Fig. 1 (dashed line) are shown here for a section of the inner eastern spiral arm in M83. The horizontal bar at the lower left indicates 30 arc s, corresponding to 530 pc or 1,280 pc along the major axis of M83 for assumed distances of 3.7 and 8.9 Mpc, respectively. The arrows marked 1 and 2 indicate the pre- and post-shock gas flow. *b*, Contours of surface density of atomic hydrogen at 10 arc s resolution, along with the H I ridge line (dashed) from the 25 arc s map of Fig. 1. *c*, Peaks of H I (solid contours), H β (dashed contours) and dust lanes in the eastern arm of M83.

Allen, Atherton, & Tilanus 1986, Nature, 319, 296

A novel explanation ...

- A simple explanation is to consider the HI not as a *precursor* to the the star formation process in spiral arms, but as a *photodissociation product* of it (Allen et al 1986, Heiner et al, etc.).
- Offsets of this kind have now been found in several nearby spirals when data with sufficient angular resolution is available (M51, M83, M100).
- There is another issue with HI: HI profiles in the Galaxy frequently show the characteristics of *high optical depth*.

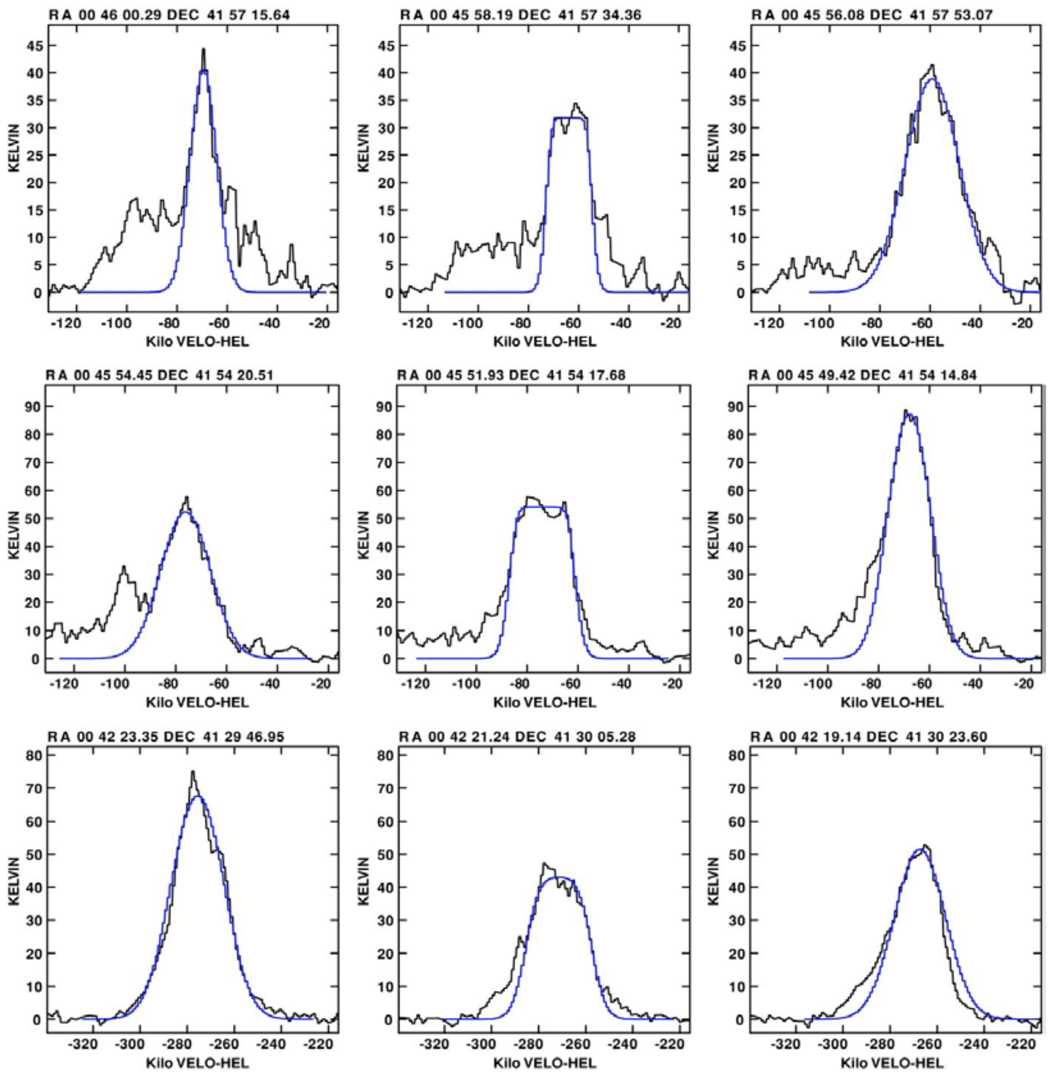
“Saturated” HI profiles in the Galaxy …



Dwingeloo 25m radio telescope FWHM ≈ 0.5˚

Hartmann et al. 1997

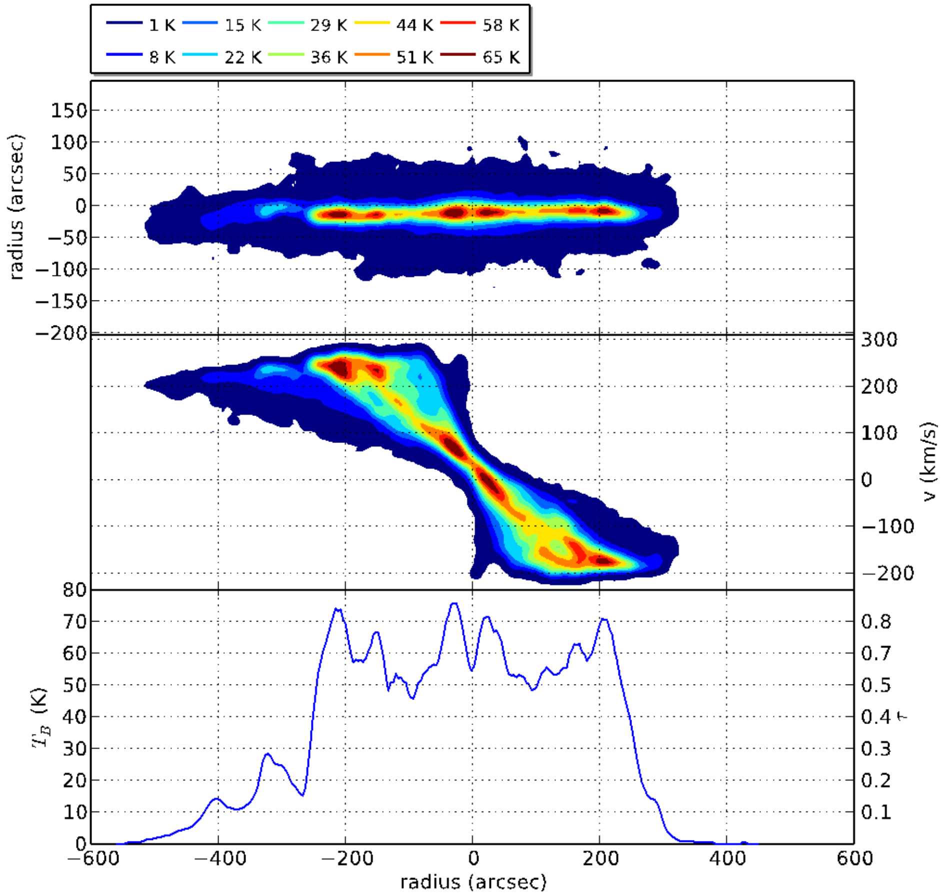
... are now also found in M31 ...



- HI frequently shows the "flat-topped" profiles characteristic of high optical depth.
- This is familiar from the Galaxy, but has now been seen in M31, M33, and the LMC *(Braun 2012)*

Braun et al. 2009 ApJ, 695, 937, (Fig. 9)

... and especially in edge-on galaxies.



NGC 891

Peters 2012 (p.c.)

So HI mass estimates are uncertain ...

- "...opacity corrections could locally exceed an order of magnitude in the implied HI column density [in M31] and that these resulted in a 30% increase in the global HI mass estimate." *(M31 - Braun et al 2009; M33 + LMC - Braun 2012; etc.)*
- HI is perhaps not quite the "simple" tracer for the large-scale ISM distribution and kinematics we have assumed ...

So HI mass estimates are uncertain ...

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- HI is perhaps not quite the "simple" tracer for the large-scale ISM distribution and kinematics we have assumed ...
- What about the usual molecular tracers?

The current gold standard is CO(1-0)

- Many observers and some theorists have argued for a standard conversion factor from the observed integrals over the 3-mm CO(1-0) line to a column density of H_2 , the "X-factor".
- This approach is widely used, and our current view of the molecular ISM in galaxies is essentially entirely based on CO(1-0) observations and a "canonical" X-factor.
- However, here also there may be more ...

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A remarkable discovery…

Unveiling Extensive Clouds of Dark Gas in the Solar Neighborhood

Isabelle A. Grenier,[1*] Jean-Marc Casandjian,[1,2] Régis Terrier[3]

From the comparison of interstellar gas tracers in the solar neighborhood (HI and CO lines from the atomic and molecular gas, dust thermal emission, and γ rays from cosmic-ray interactions with gas), we unveil vast clouds of cold dust and dark gas, invisible in HI and CO but detected in γ rays. They surround all the nearby CO clouds and bridge the dense cores to broader atomic clouds, thus providing a key link in the evolution of interstellar clouds. The relation between the masses in the molecular, dark, and atomic phases in the local clouds implies a dark gas mass in the Milky Way comparable to the molecular one.

2005 Science, 307, 1292

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2005 Science, 307, 1292

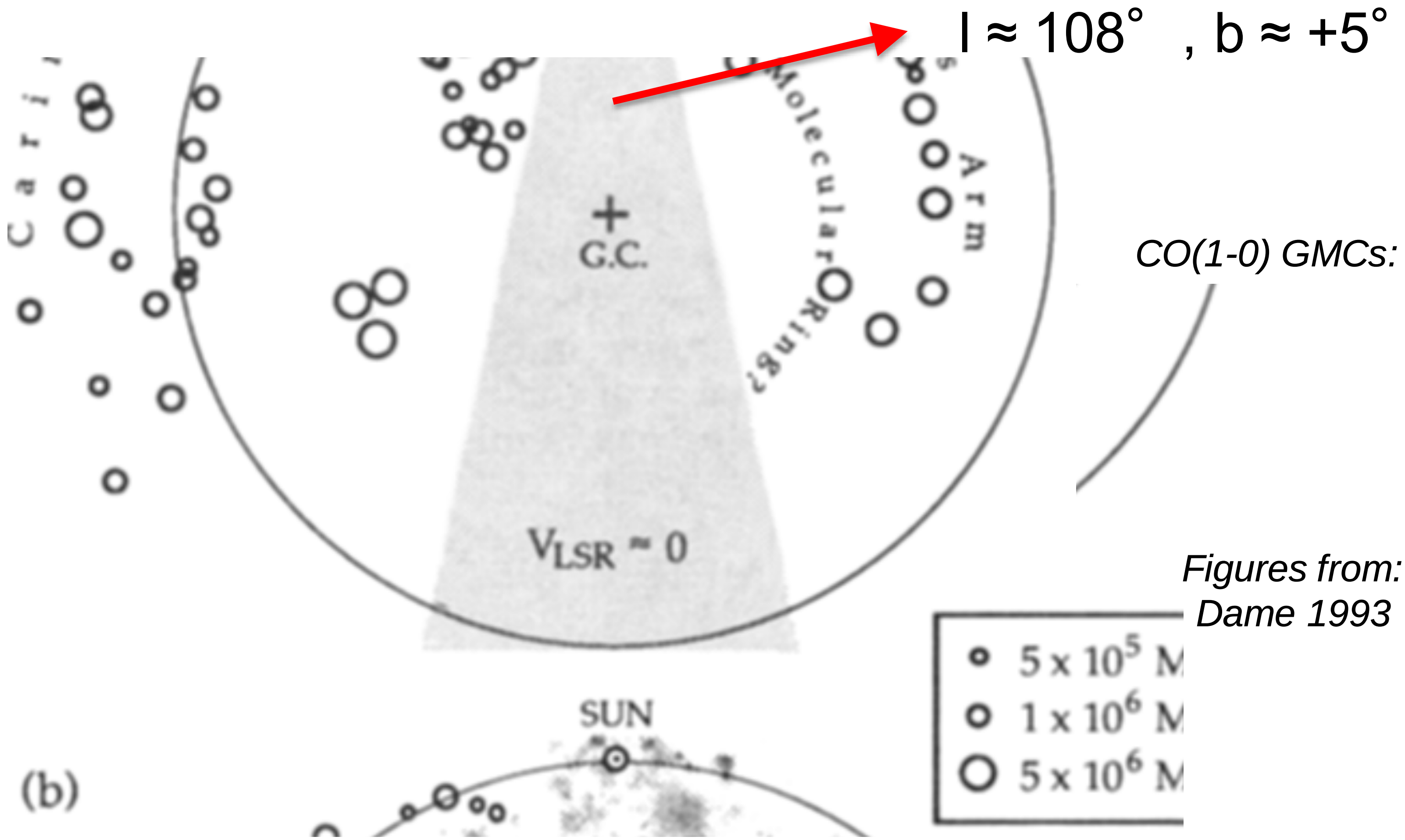
... and an unexpected connection ...

A mini-survey for 1667 MHz OH emission from the general ISM in the Outer Galaxy

Ron Allen, Monica Rodriguez,
John Black, & Roy Booth

(2012 AJ, 143, 97 & 2013 AJ, 145, 85)

LOS chosen towards the Outer Galaxy …



CO(1-0) GMCs:

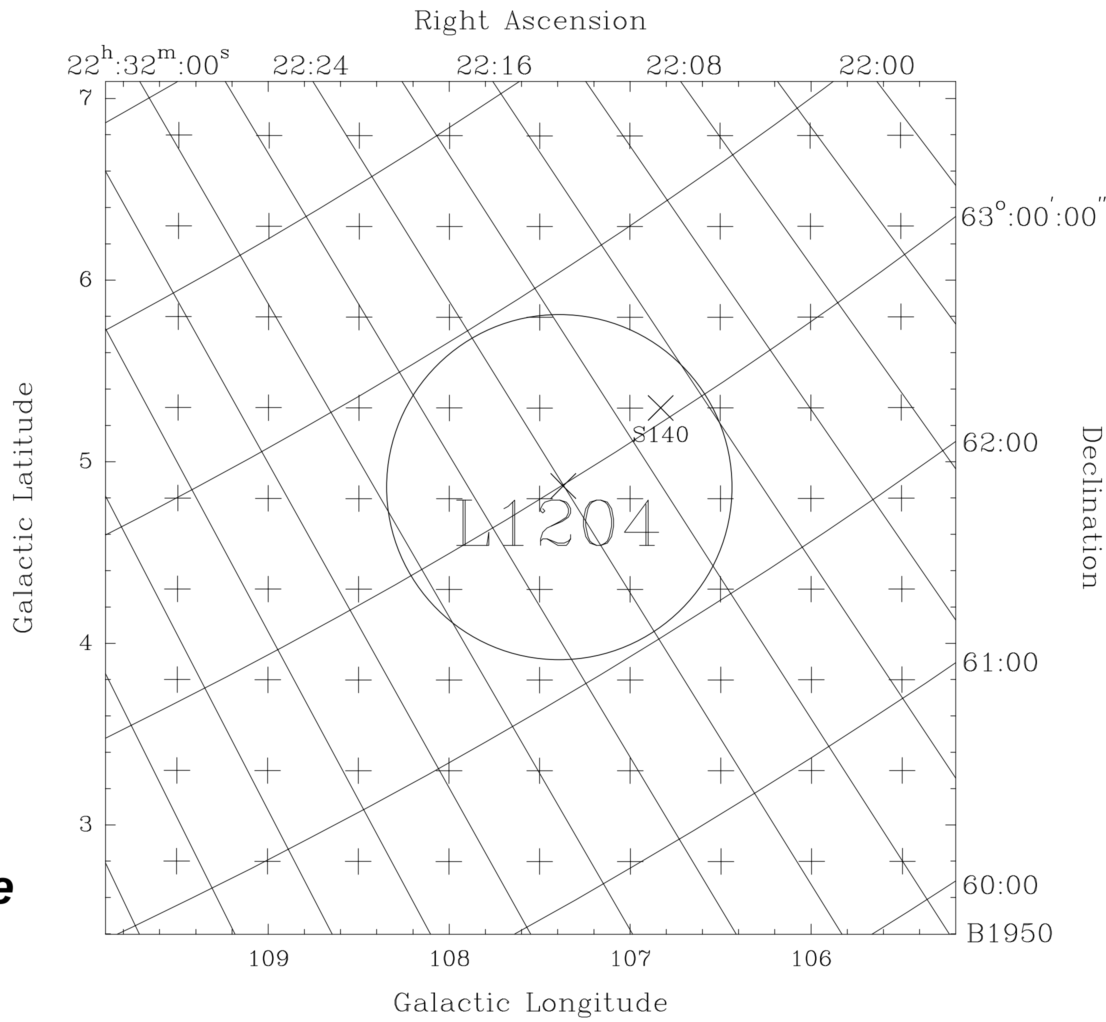
Figures from: Dame 1993

Allen, Rodriguez, Black, & Booth 2012, AJ, 143, 97

Galactic structure

– At this longitude ($l \approx 108°$), distance is nearly linearly-related to radial velocity, as:
  - D(pc) ≈ -120 V_{LSR}(km/s)
– The LOS exits the Galactic disk beyond $V_{LSR} \approx -20$ km/s for the typical survey area latitude ($b \approx +5°$).
– A modest total spectral coverage can provide path lengths of ≈ few kpc.
  - This should provide an idea of the 1D filling factor.

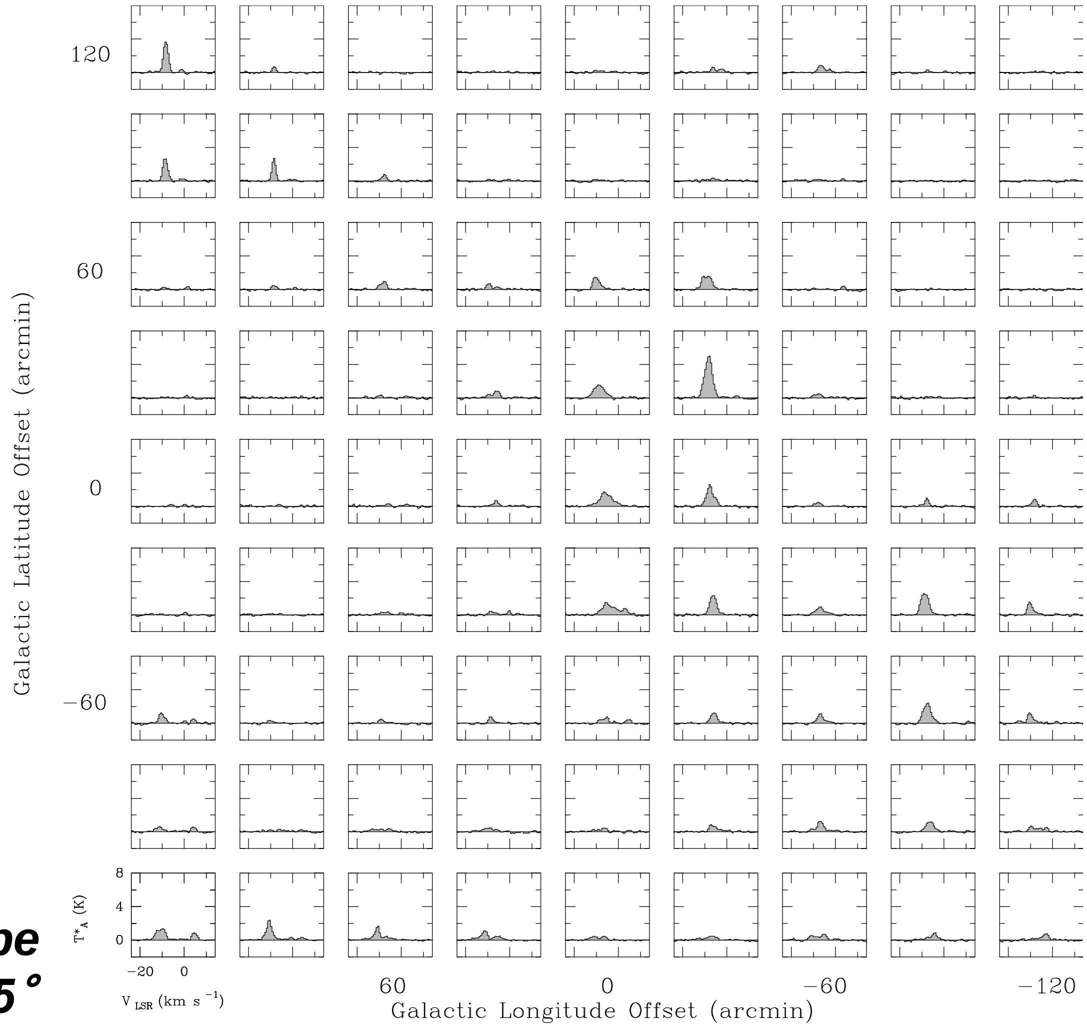
Survey area surrounds Lynds 1204 …



ONSALA 25m radio telescope FWHM ≈ 0.5°

Allen et al 2012, AJ, 143, 97

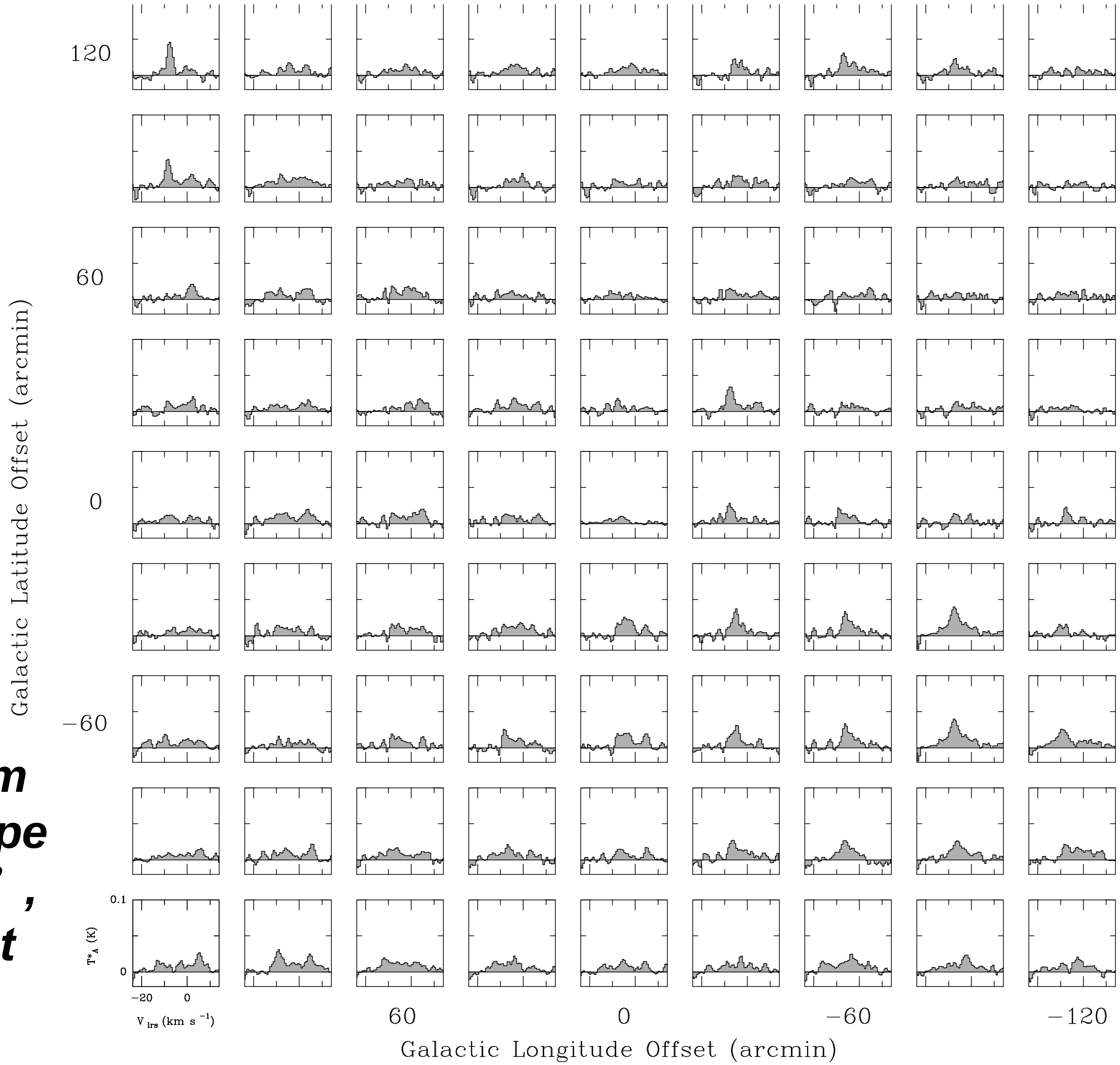
… and has spotty CO(1-0) emission …



CfA 1.2m radio telescope smoothed ≈ 0.5°

Dame 2012 (priv. comm.)

… but OH 1667 emission is *everywhere* …

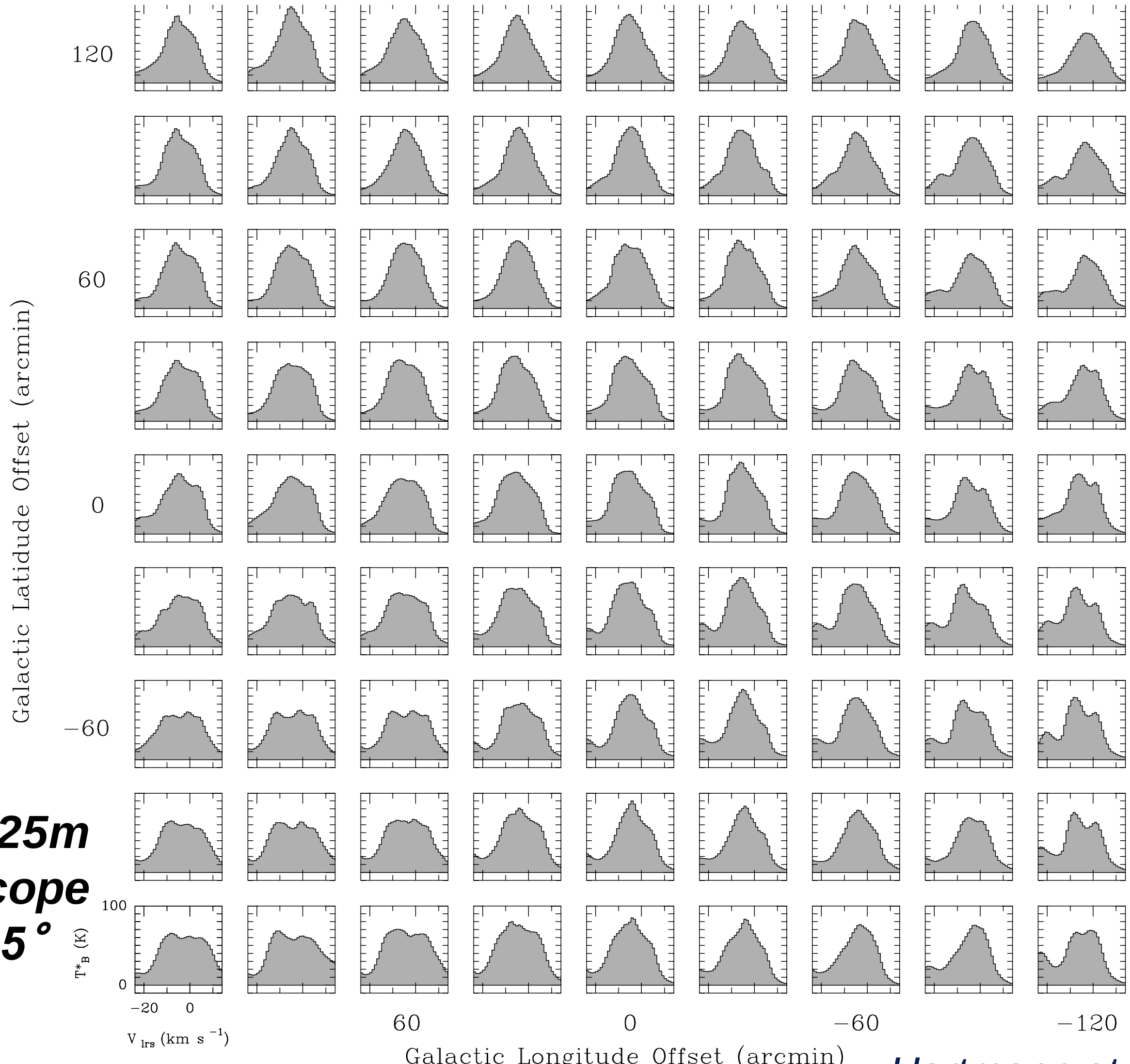


ONSALA 25m radio telescope FWHM ≈ 0.5° , ≈ 3 hrs/point

Allen et al 2012, AJ, 143, 97

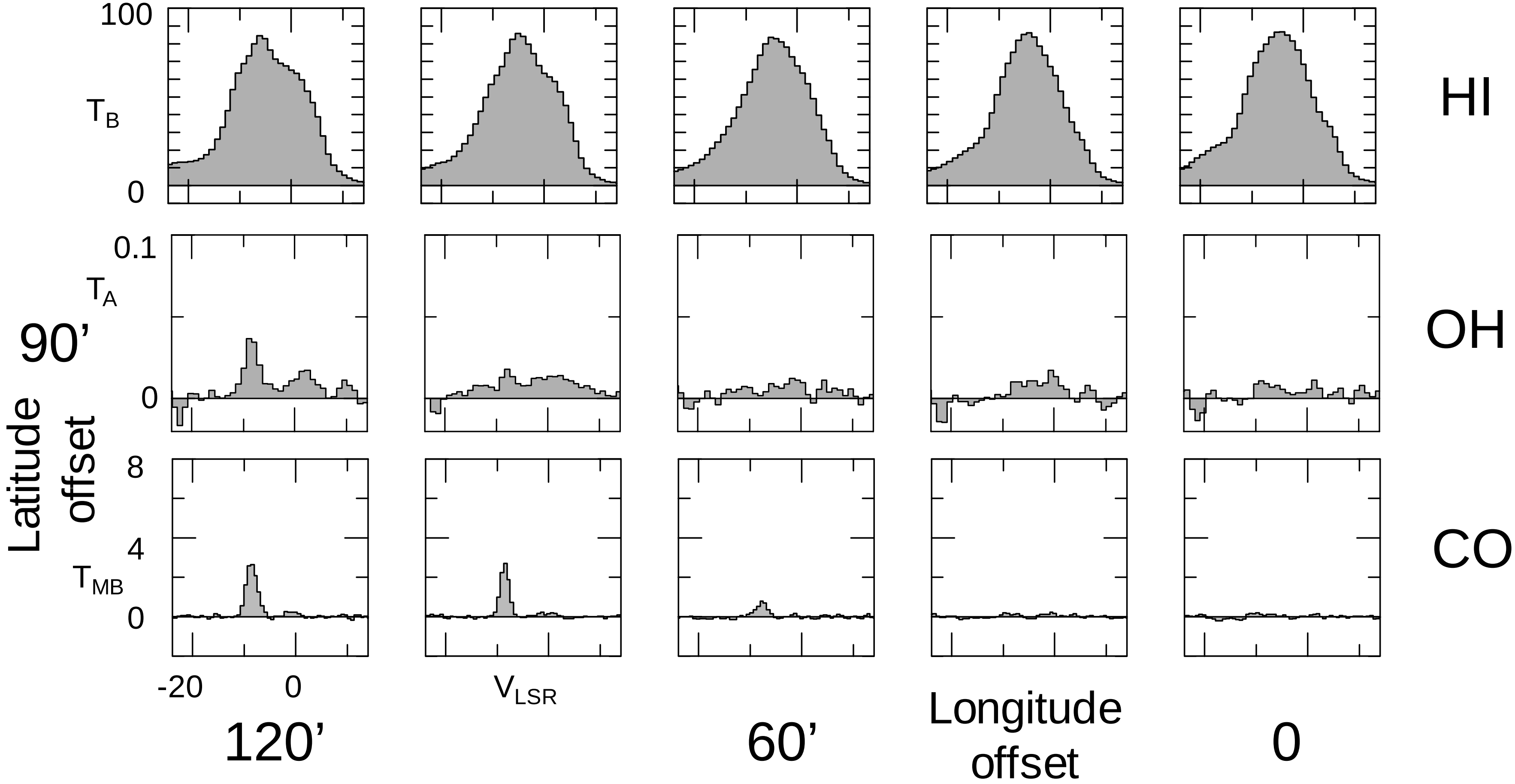
… and has the velocity extent of the HI.

Dwingeloo 25m radio telescope FWHM ≈ 0.5˚



Hartmann et al. 1997

Some profile details ...



H_2 column from CO …

- $N(H_2)$ from 3-mm CO emission:
  - $N_{CO}(H_2) \approx 2 \times 10^{20}\ T_{MB}\,(CO)\,\Delta V$ K•km/s
  - This uses the infamous "X Factor" for CO(1-0), based ultimately on the Virial Theorem (and the topic of much grumbling …)

H_2 column from OH …

- Usual method is to get N(OH) from the radio spectroscopy and use an assumed abundance to infer N(H_2) …
- Absorption-line spectroscopy of UV-bright stars in the solar neighborhood offers a more direct method:
  - Copernicus and FUSE results for H_2
  - UVES results for OH (Weselak et al 2009, A&A 499, 783)
  - data presently scarce but could be extended

The OH – H_2 correlation …

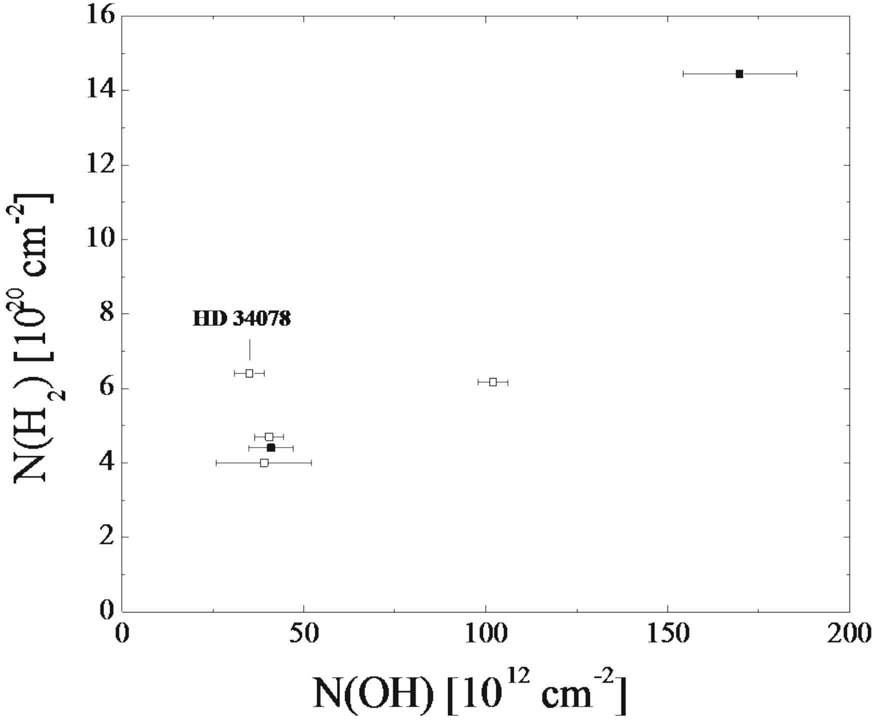


Fig. 5. Interstellar H_2 column density (from the literature) vs. that of OH. Filled squares – our measurements; open squares – the literature data. Note HD 34078 – the object probably also lies outside the relation between column densities of H_2 and OH.

Weselak et al 2009

Molecular column from OH …

- The data are clearly still a bit sparse, but tantalizing, and more needs to be done.
- If this correlation proves robust, then we have a direct measure of $N(H_2)$ from 18-cm OH line emission … an "X-Factor" for OH:
  - $N_{OH}(H_2) \approx 34 \times 10^{20}\ T_B(OH)\ \Delta V$ K•km/s

Results in the survey area …

- Total number of survey positions: 81
- Number showing CO emission:
  - 56, at present levels of sensitivity (25 are below the detection level)
- Number of positions showing OH emission:
  - All 81, at present levels of sensitivity
- Average $N_{CO}(H_2)$ over all 81 survey positions:
  - 7.8×10^{20} in compact components
- Average $N_{OH}(H_2)$ over all 81 survey positions:
  - 10.1×10^{20} in extended components having little overlap with CO

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Some conclusions: OH and CO …

- Only ≈10% of the *compact* OH features show CO emission.
  - When they do, the H_2 columns implied by the 18-cm OH emission data are similar to those inferred from X_{CO}.
  - When they don't, CO molecules are either absent, or the 3-mm emission is insufficiently excited to be observed.
- Over the survey area, the OH emission implies that:
  - *there is more than twice as much molecular gas in the Galaxy as is revealed by CO, and this gas is more widely distributed.*

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  - *there is more than twice as much molecular gas in the Galaxy as is revealed by CO, and this gas is more widely distributed.* **This agrees with the Grenier et al result.**
- OH appears to be a kinematic tracer for the dark gas in the Galaxy. *The dark gas itself is likely to be H_2* .

Some new puzzles …

- OH and HI appear to co-exist in the Galaxy, but nothing is known about the relative abundances of molecules e.g. in the inner vs. the outer Galaxy.
- This needs to be examined further with more extensive OH surveys, but the signals are faint and a lot of observing time will be required.
- This widespread molecular component suggests that a photodissociation – reformation cycle based on *ambient* UV and dust grains may account for significant amounts of HI everywhere in the ISM, and not just in spiral arms as was suggested by AAT almost 30 years ago.

Some personal conclusions ...

- Definitive observational tests of Density Wave theory are easier to describe than to achieve.
- The physics of the ISM tracers we use cannot be ignored when studying the large-scale properties of spiral structure in galaxies.
- In astronomy, attempting to test a theory with observations can turn into a lifetime job.

Spiral skaters - 1974

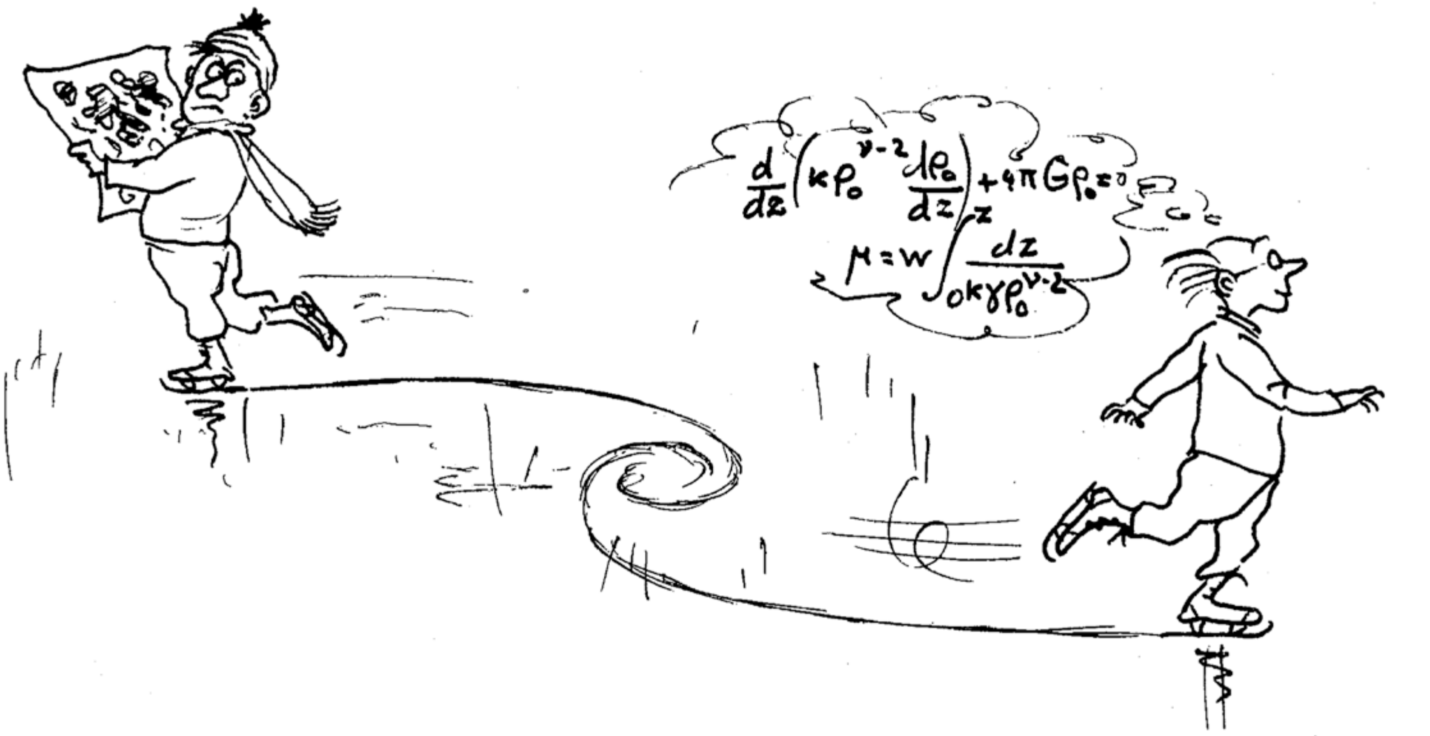

Illustration de J.P. PETIT, participant au Colloque

“La Dynamique des Galaxies Spirales”, IHES Bures-sur-Yvette 1974

The End (for today)

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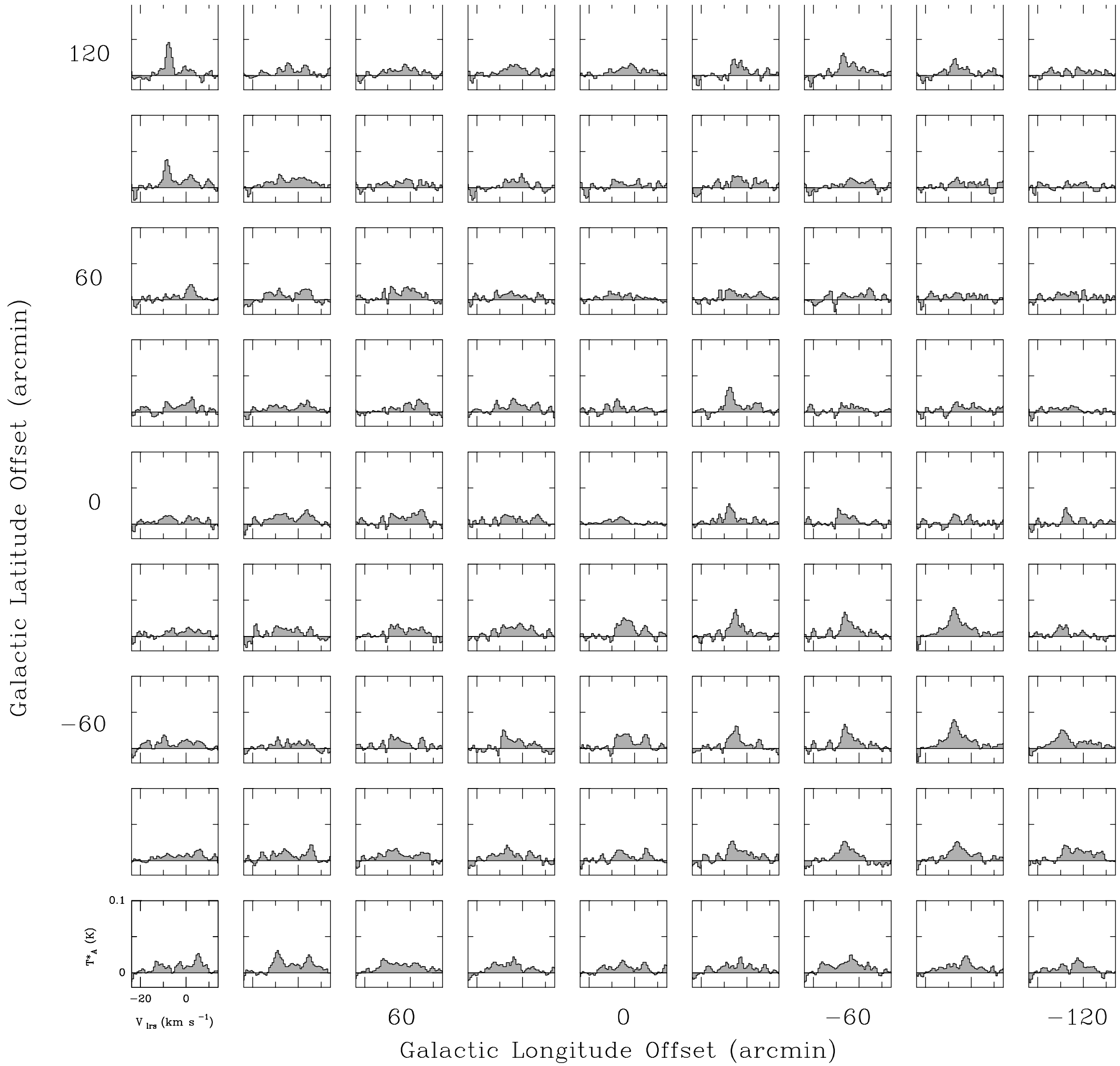
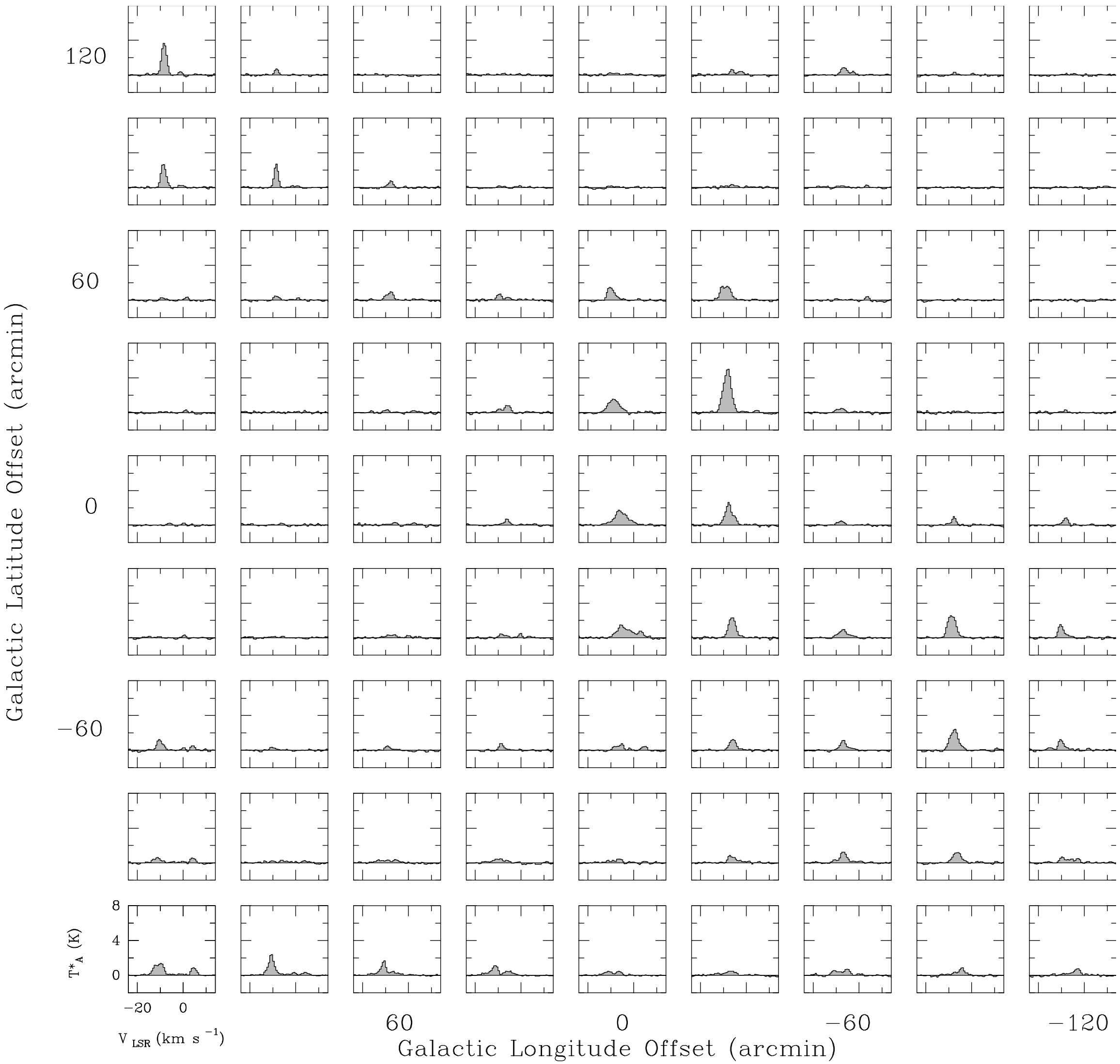
BACKUP SLIDES

OH 1667 is different from 3-mm CO …



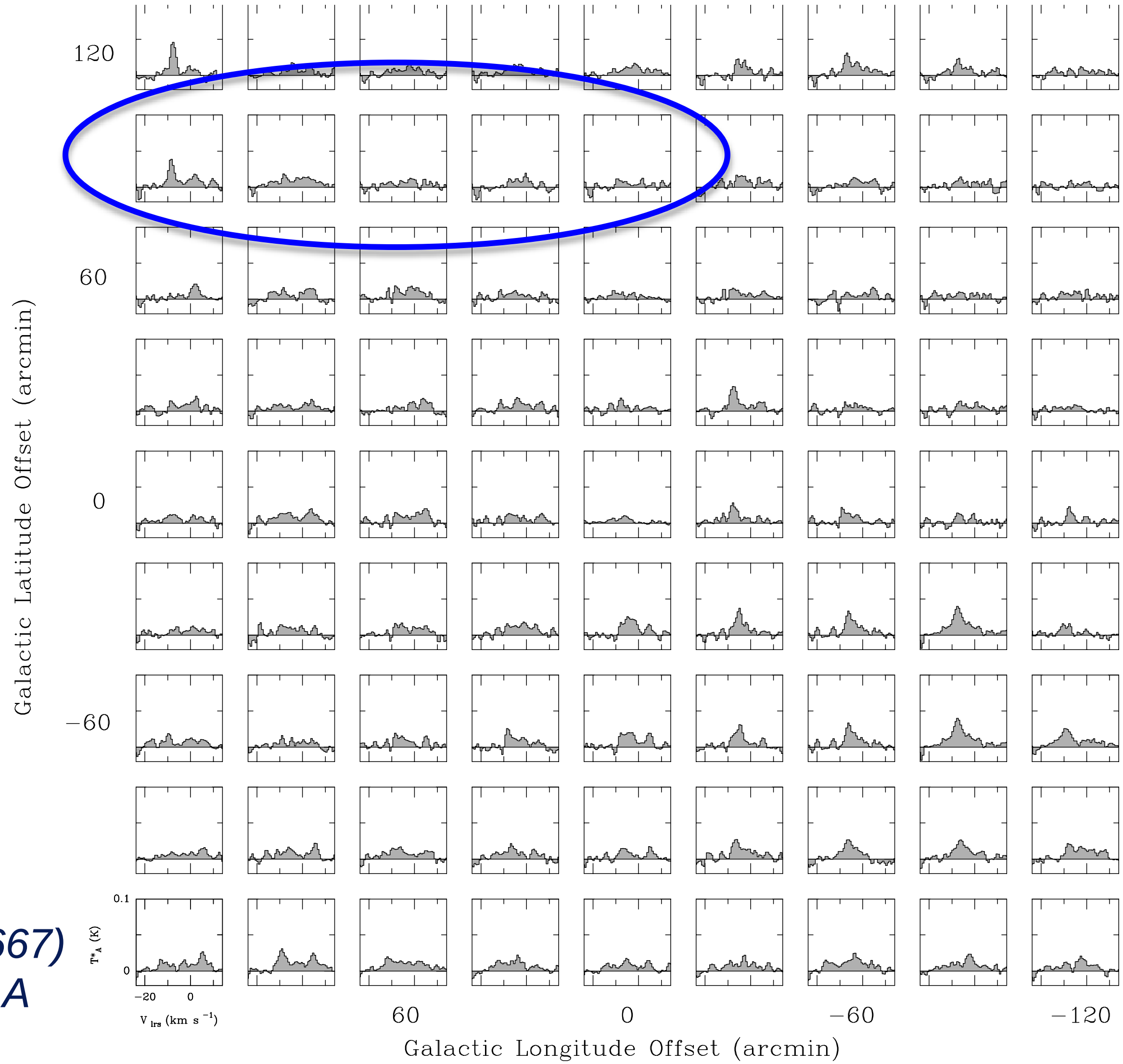
Allen et al 2012, AJ, 143, 97

… CO(1-0) …



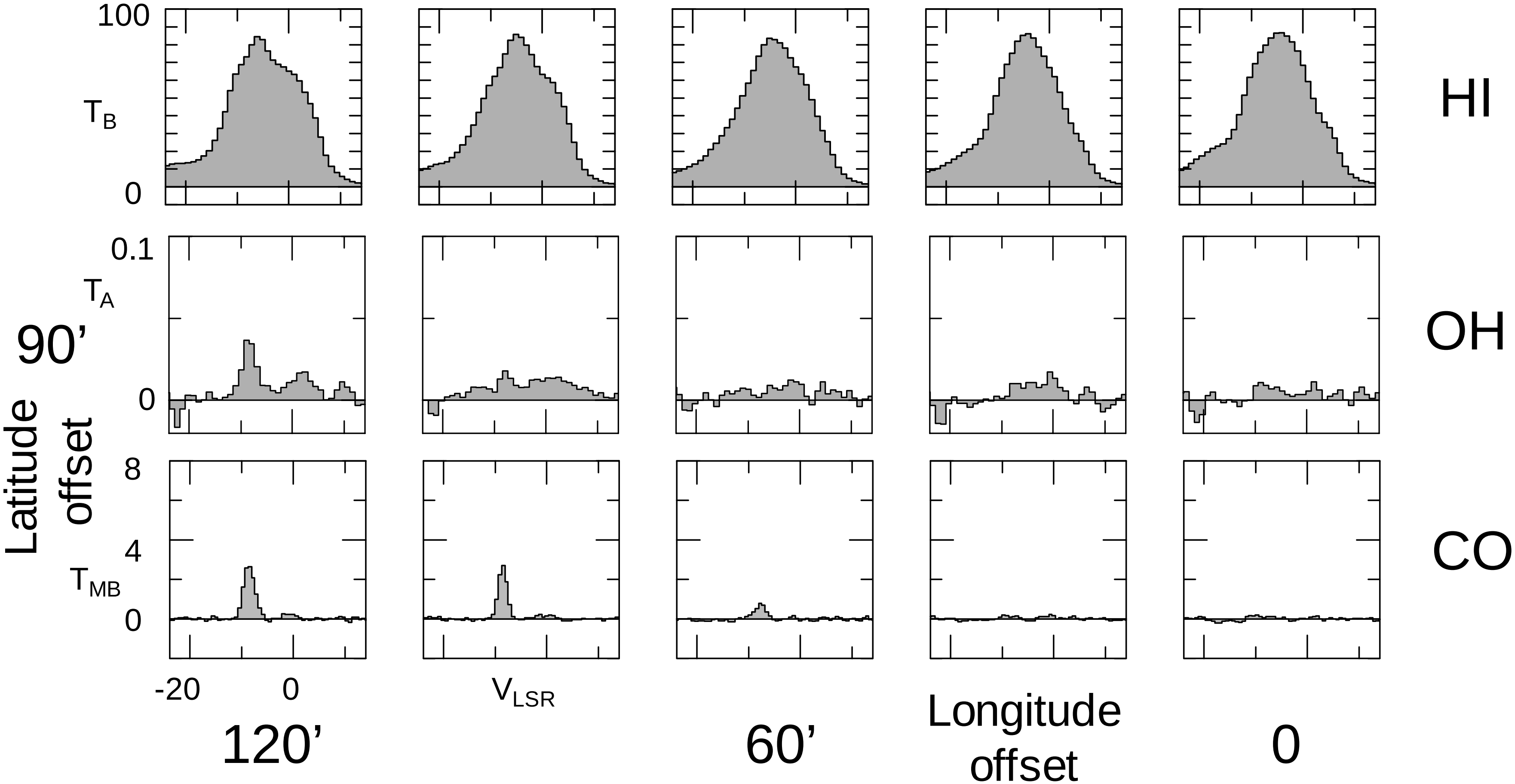
Dame 2012 (priv. comm.)

Let's take a closer look …



Faint OH(1667) at ONSALA

… at the profile details:



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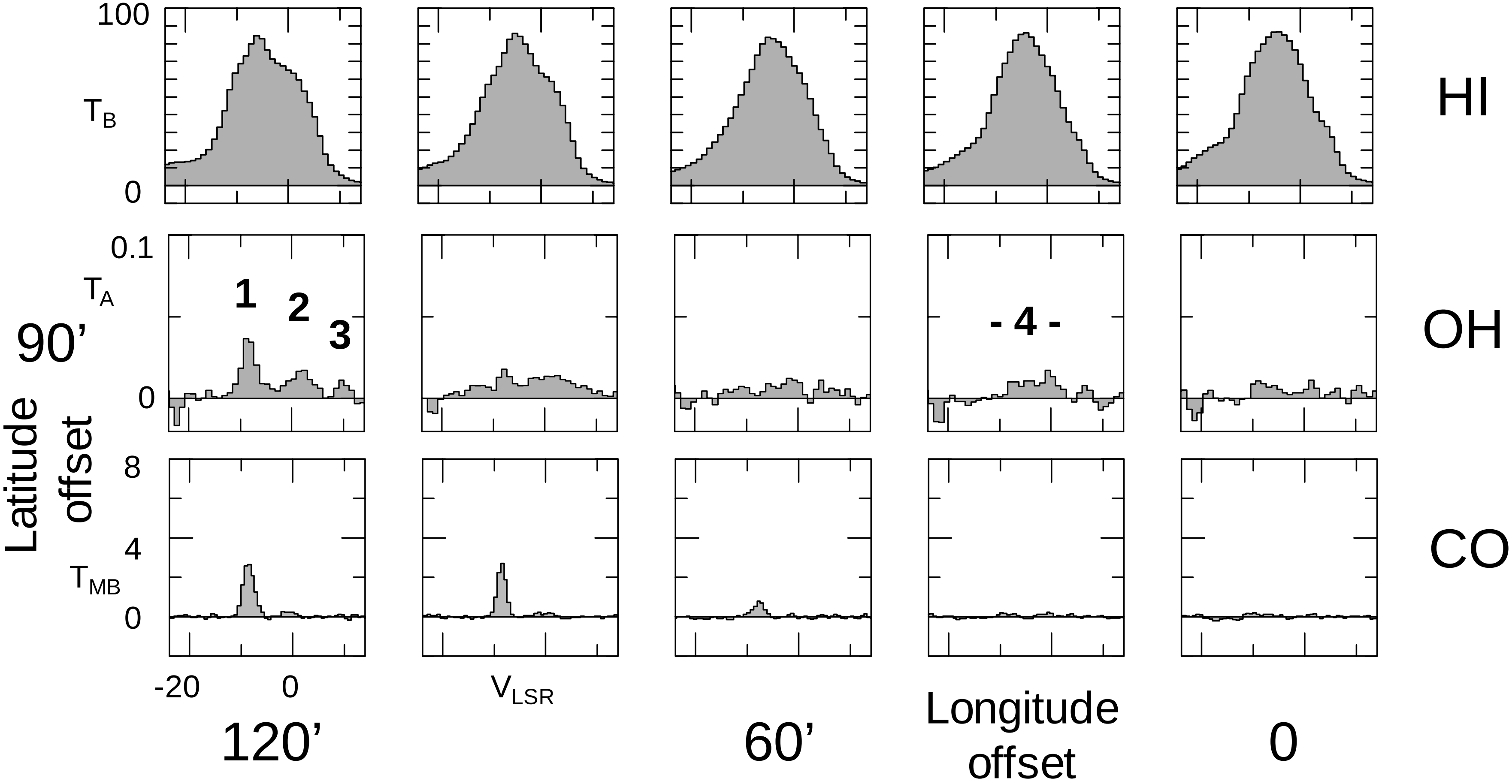

Typical H_2 column densities in specific similar velocity "features" …

Feature	Tb(OH)	Tmb(CO)	ΔV	NH2(OH)/10^20	NH2(CO)/10^20
1	30 mK	2.5 K	3 km/s	3.1	15
2	20	≤ 0.3	4	2.7	≤ 2.5
3	10	≤ 0.15	2	0.7	≤ 0.6
4	≈ 15	Not detected	≈10	≈ 5	Not detected

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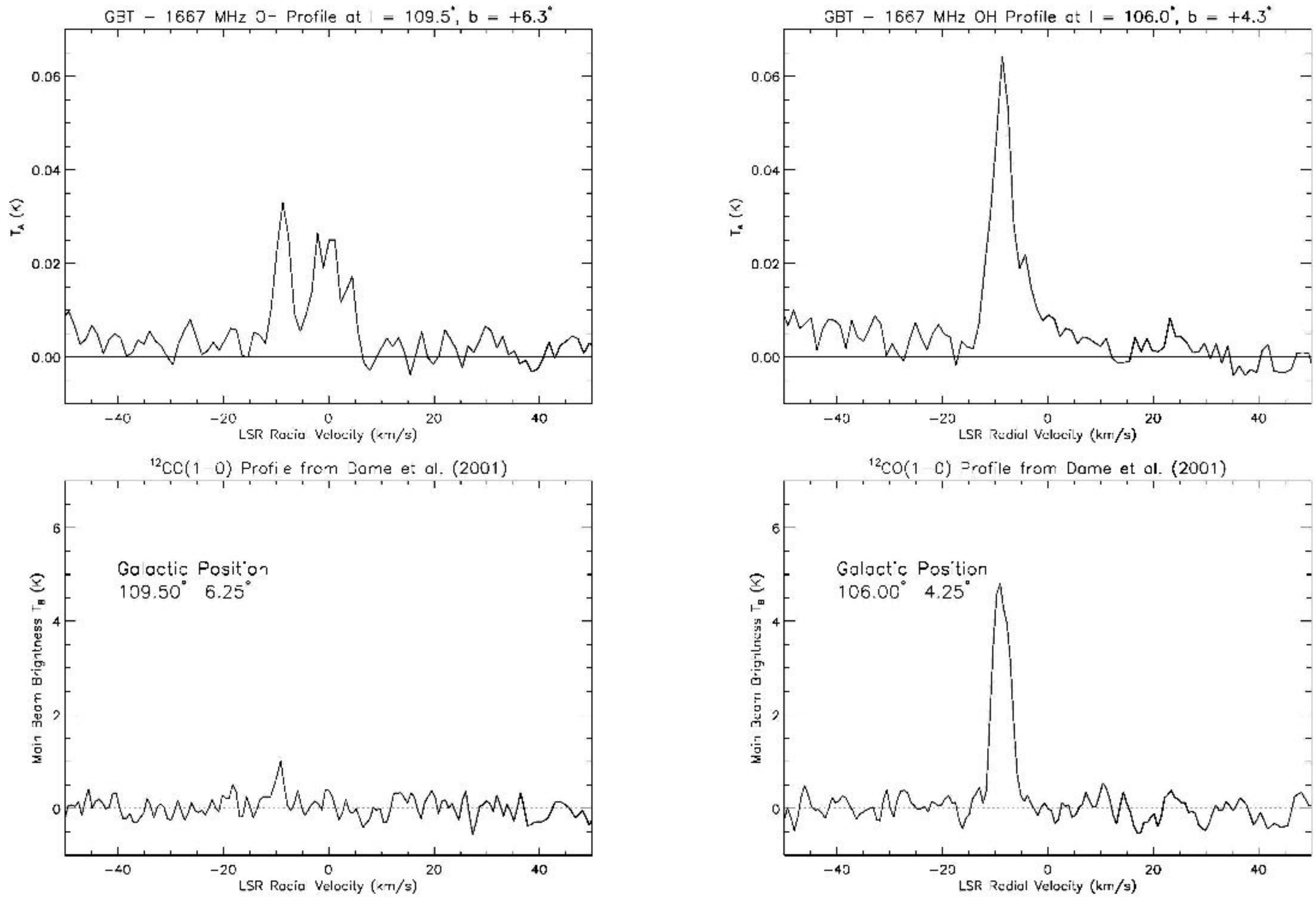


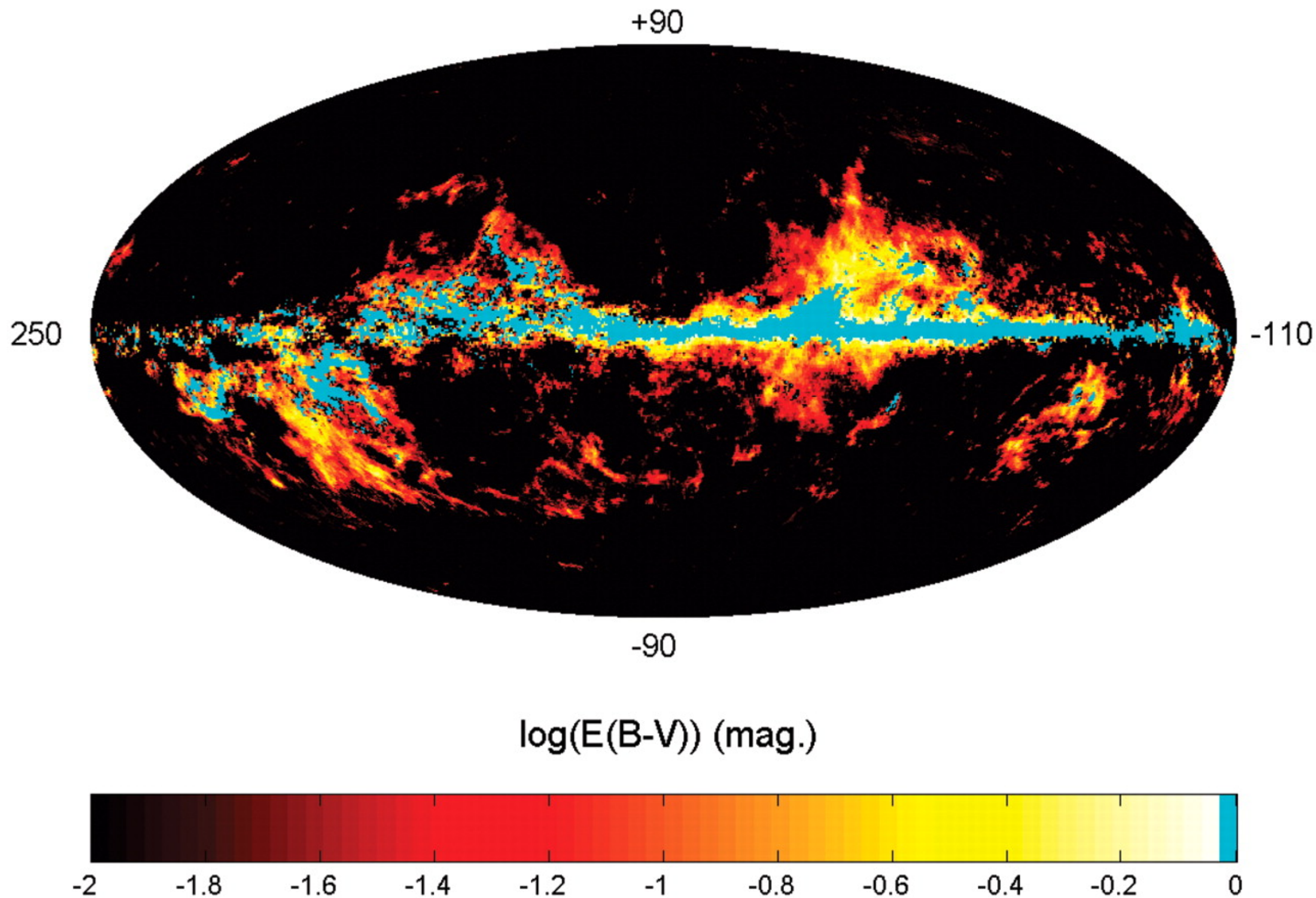
Fig. 2.— **Upper left:** GBT spectrum of the **1667** OH line recorded at $l = 109.5°,\ b = +6.3°$ ("POS1") in 3.5 hr. **Upper right:** GBT spectrum of the 1667 OH line recorded at $l = 106.0°,\ b = +4.3°$ ("POS2") in 1.3 hr. **Lower left:** CfA spectrum of the 3-mm CO line recorded at $l = 109.5°,\ b = +6.25°$ (near "POS1"). **Lower right:** CfA spectrum of the 3-mm CO line recorded at $l = 106.0°,\ b = +4.25°$ (near "POS2") Note that the angular resolution of $\approx 8'$ is nearly identical for all 4 profiles, although the OH and CO positions differ by $3'$.

A digression …

- The "streetlight effect":
  - a type of *observational bias* where people only look for whatever they are searching by looking *where it is easiest*.
    - "A policeman sees a drunken man searching for something under a streetlight and asks what the drunk has lost. The drunk says he has lost his keys, and they both look under the streetlight together. After a few minutes the policeman asks if the drunk is sure he lost his keys here. The drunk replies, no, that he lost them in the park. The policeman asks why is he searching here, and the drunk replies, "because this is where the light is."

Freedman 2010

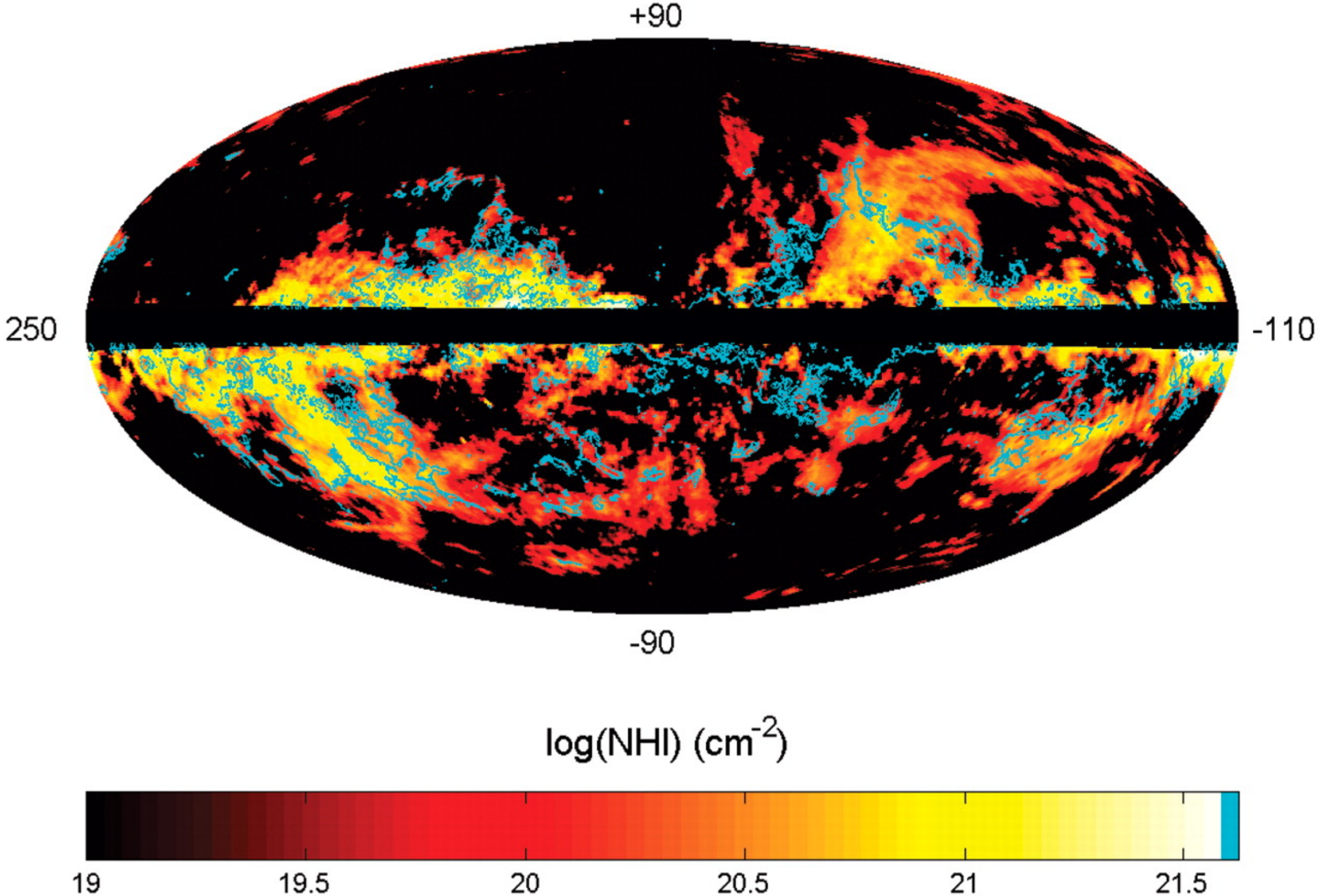
Fig. 1. Map, in Galactic coordinates centered on l = 70°, of the excess dust reddening found above that linearly correlated with the integrated HI and CO line intensities.



I A Grenier et al. Science 2005;307:1292-1295

Published by AAAS

Fig. 2. Map, in Galactic coordinates centered on l = 70°, of the HI column densities in nearby atomic clouds isolated by subtracting the Galactic disk emission from the best-fit cosecant law about the warped plane.



I A Grenier et al. Science 2005;307:1292-1295

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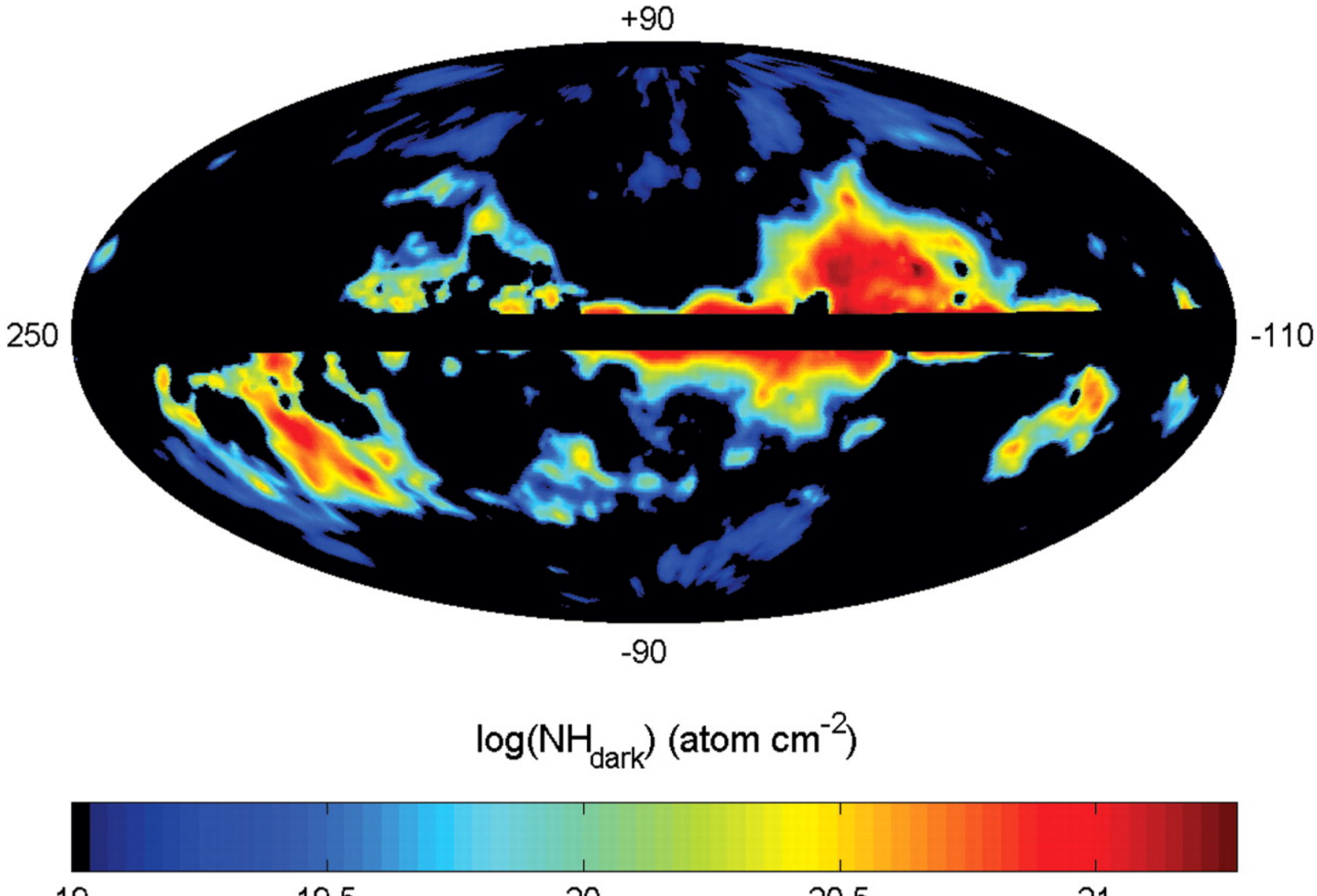
Fig. 4. Map, in Galactic coordinates centered on l = 70° , of the column densities of dark gas found in the dust halos, as measured from their γ-ray intensity with the reddening map.



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