OH and CH in the Envelopes of Young High Mass Stellar Objects

Karl M. Menten
MPI für Radioastronomie

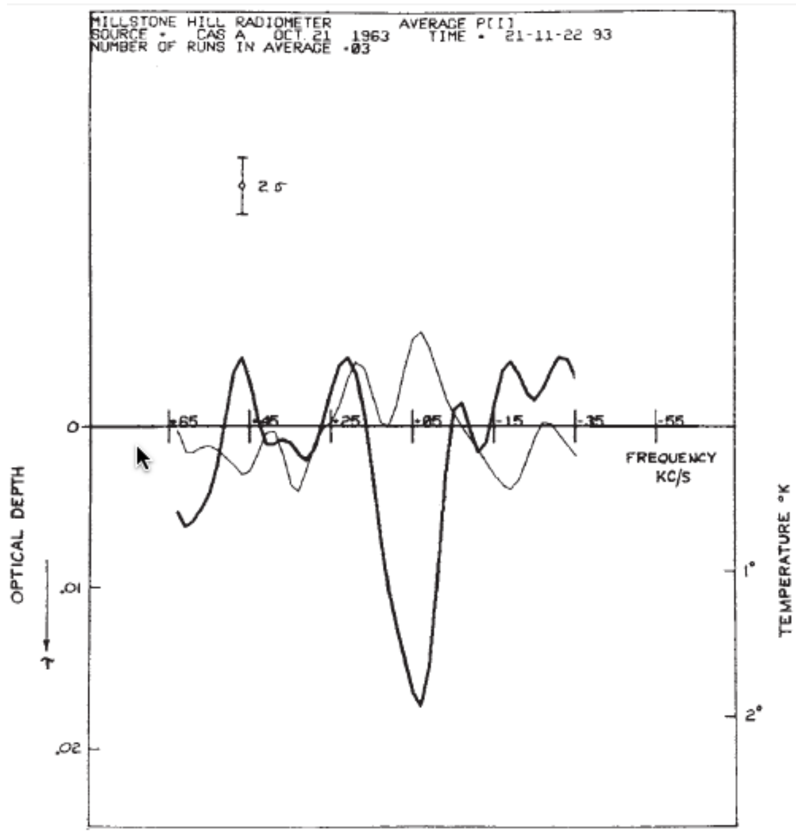
Heritage of SOFIA – Scientific Highlights and Future Perspectives

Stuttgart, April 23, 2024

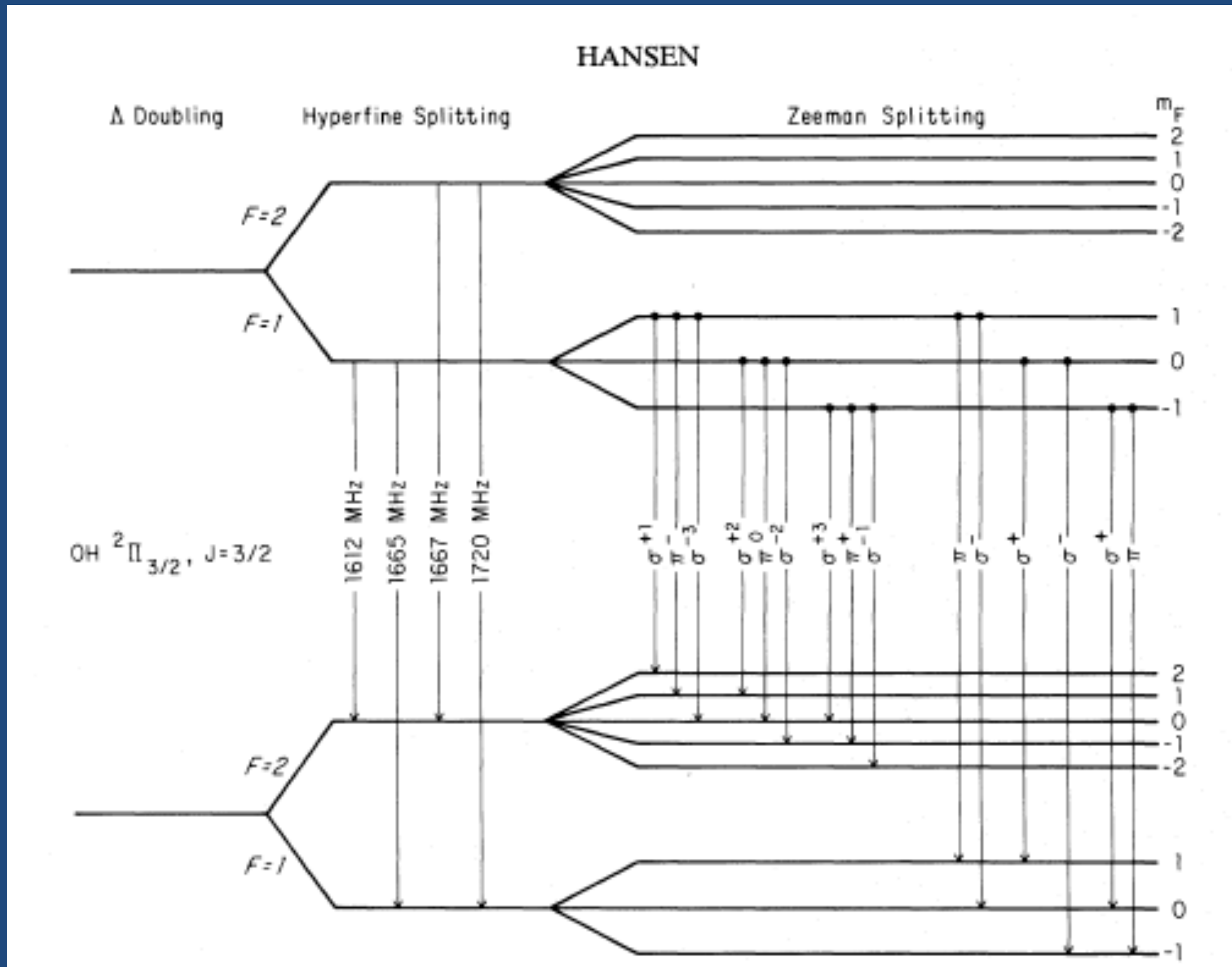
RADIO OBSERVATIONS OF OH IN THE INTERSTELLAR MEDIUM

By Dr. S. WEINREB
Lincoln Laboratory, Massachusetts Institute of Technology
Prof. A. H. BARRETT
Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Mass.
AND
Dr. M. L. MEEKS and J. C. HENRY
Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Mass.

Nature 1963



Hydroxyl (OH) $^2\Pi_{3/2}$ ground-state transitions



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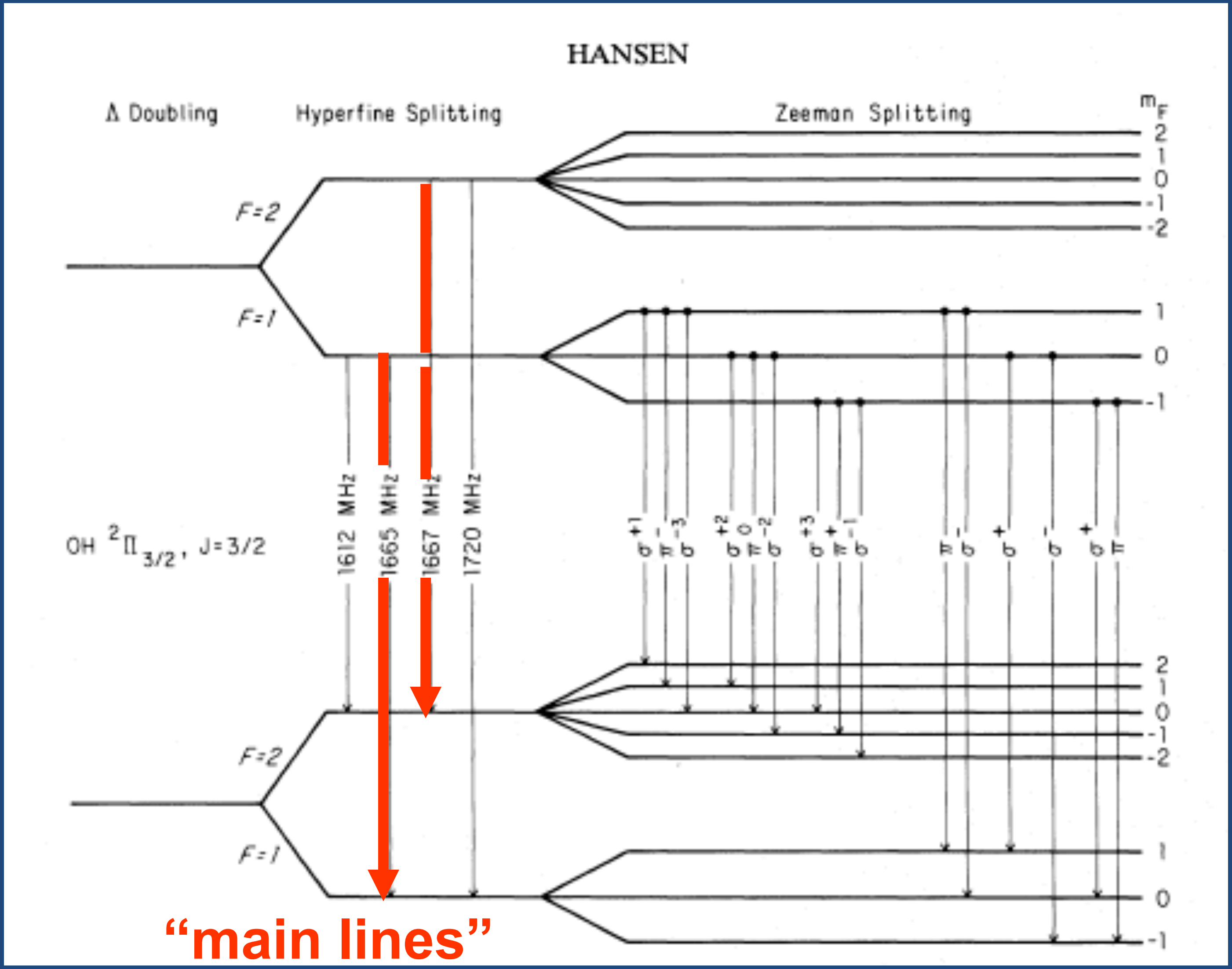

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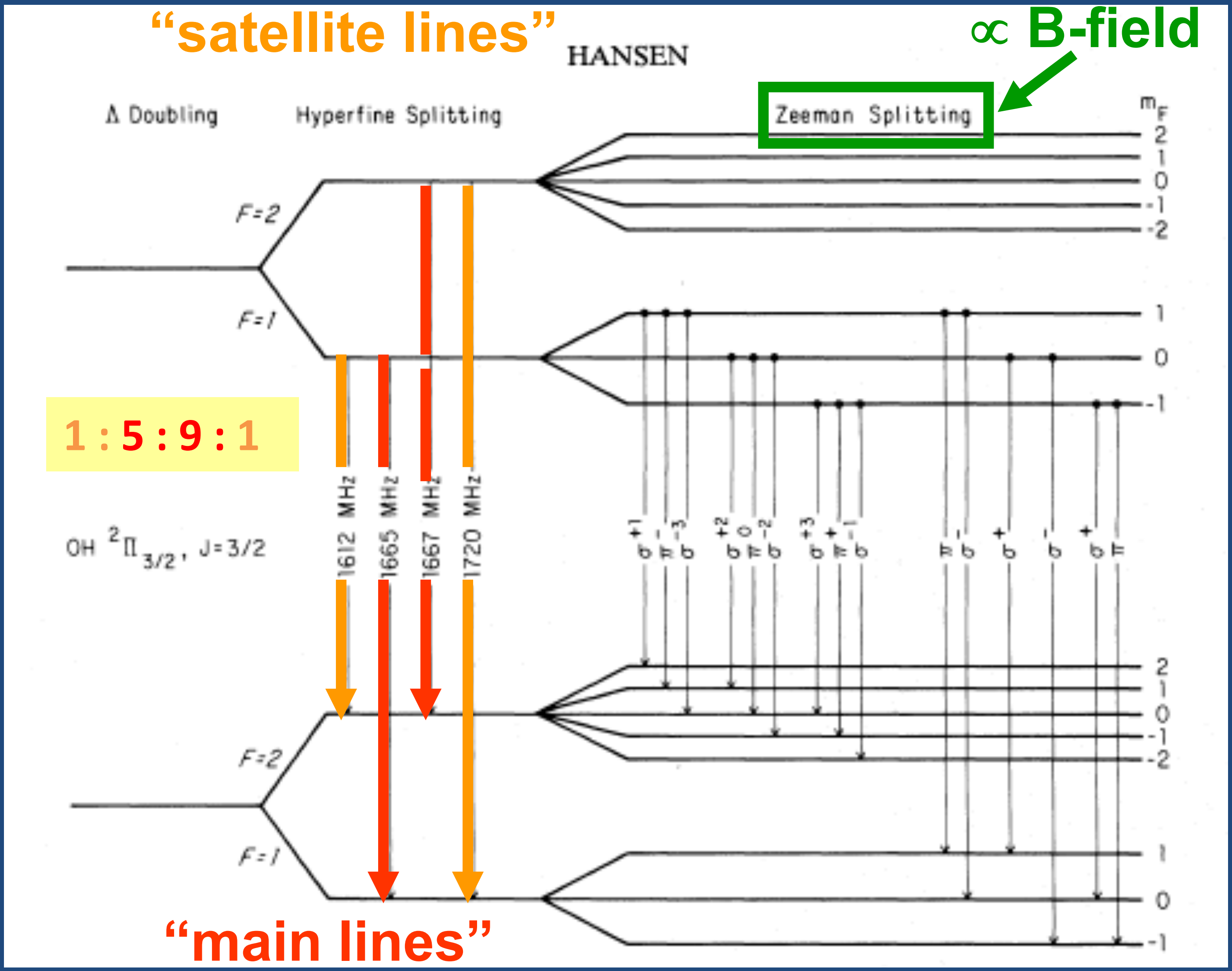

THE ASTROPHYSICAL JOURNAL, Vol. 151, March 1968

NORMAL OH EMISSION AND INTERSTELLAR DUST CLOUDS

CARL E. HEILES
Berkeley Astronomy Department, University of California

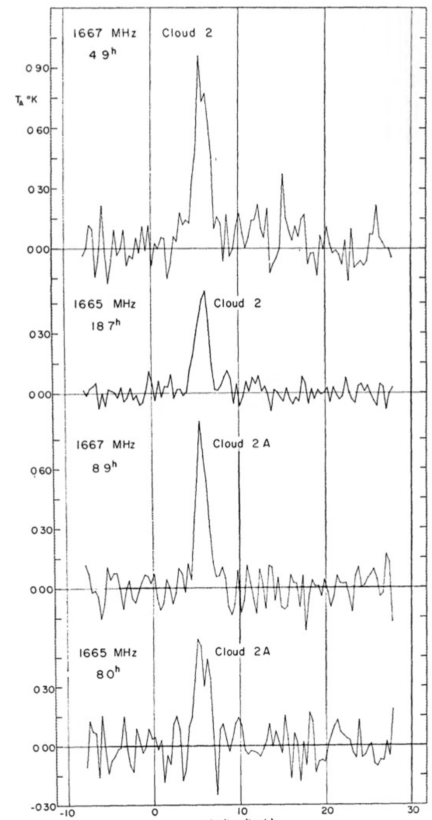

FIG. 2—*Continued*

Heiles Cloud 2

The Astrophysical Journal, 815:13 (9pp), 2015 December 10 doi:10.1088/0004-637X/815/1/13

OH 18 cm TRANSITION AS A THERMOMETER FOR MOLECULAR CLOUDS

Yuji Ebisawa[1], Hiroshi Inokuma[1], Nami Sakai[2], Karl M. Menten[3], Hiroyuki Maezawa[4], and Satoshi Yamamoto[1]
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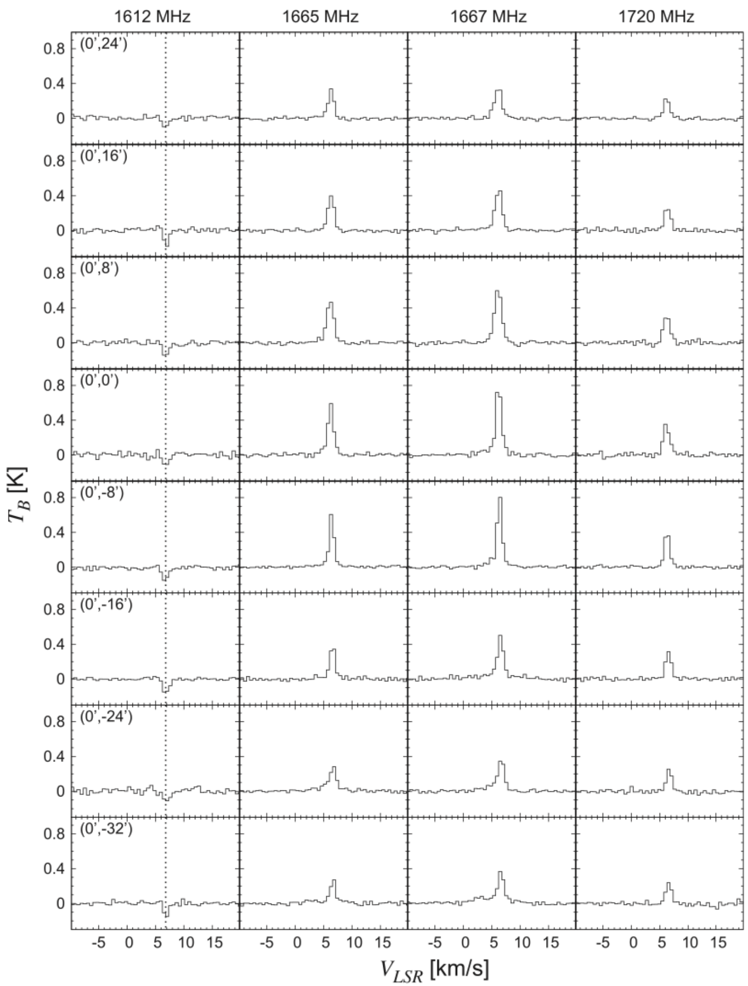
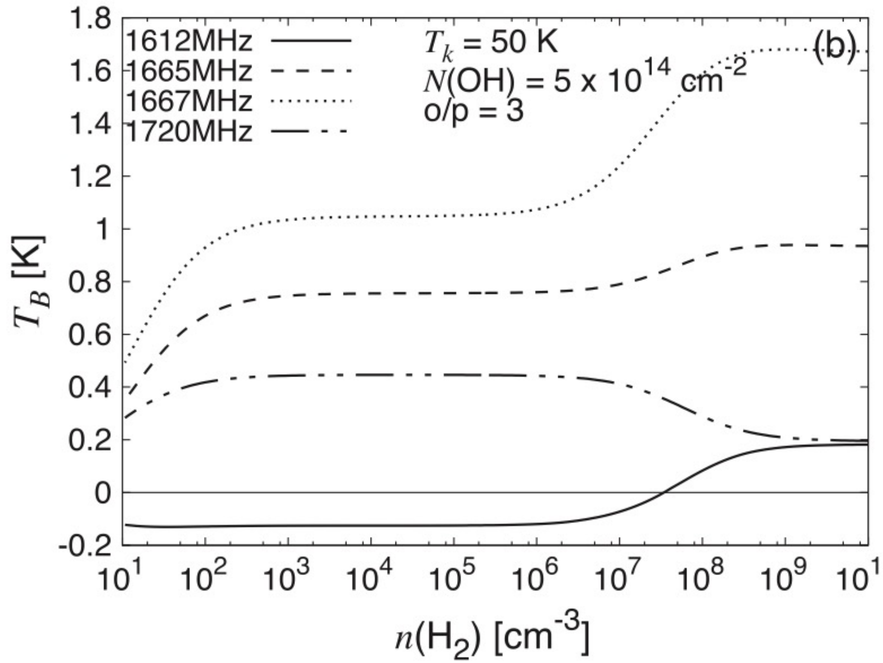
[2] RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
[3] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
[4] Department of Physical Science, Osaka Prefecture University, 1-1 Gakuen-cho, Naka-ku, Sakai, Osaka 599-8531, Japan

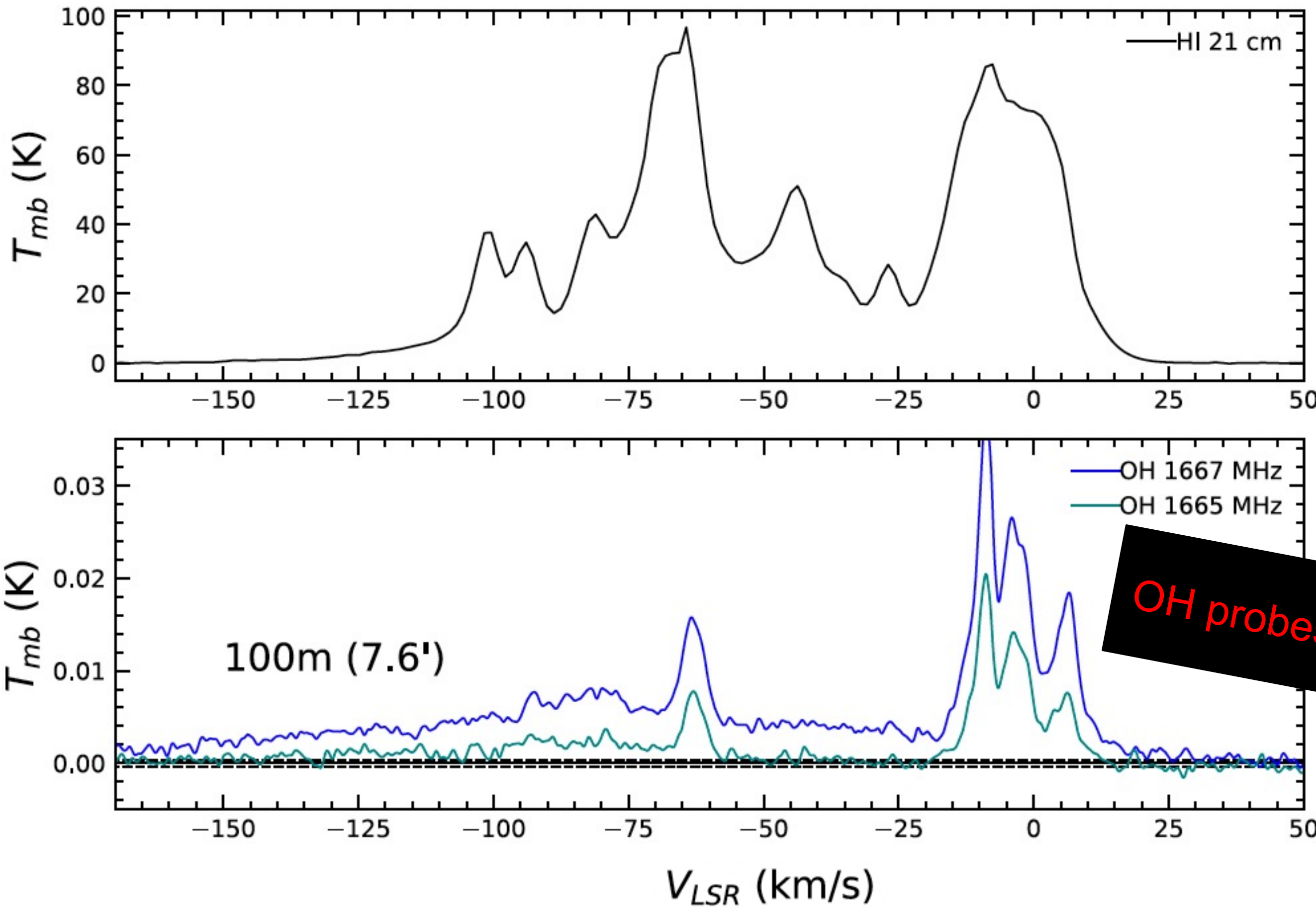




THE ASTROPHYSICAL JOURNAL, 914:72 (12pp), 2021 June 10 https://doi.org/10.3847/1538-4357/abf832

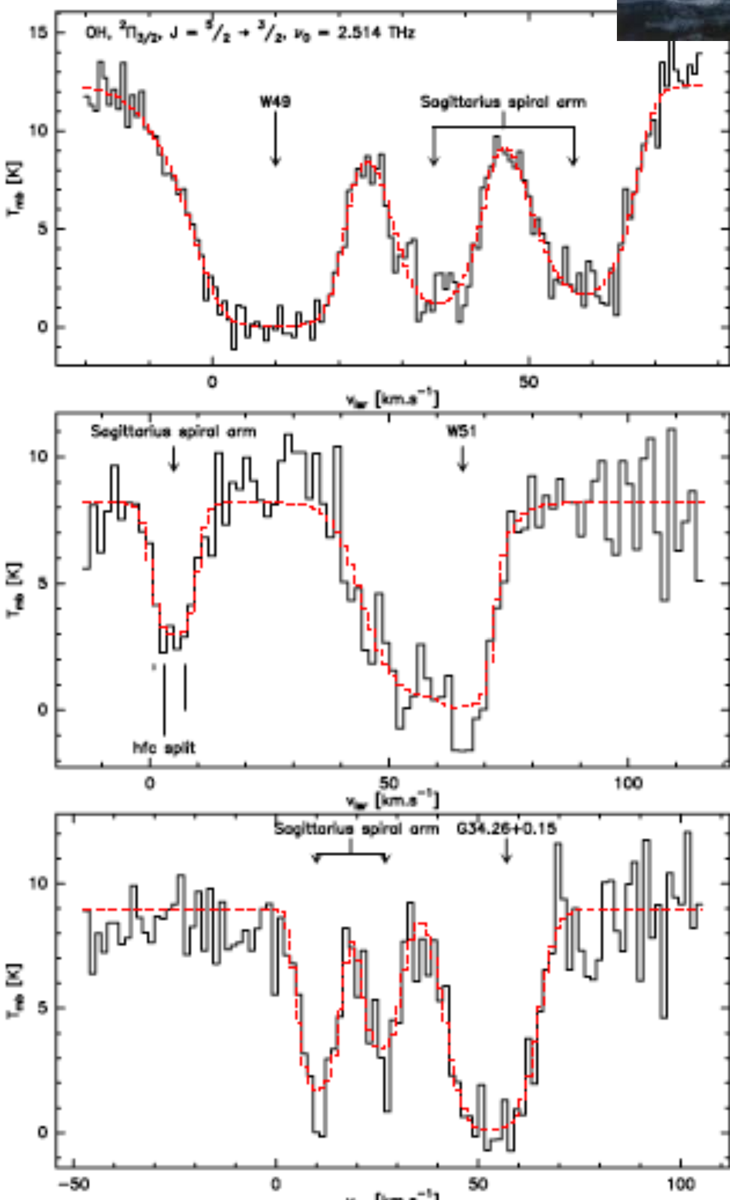
Observational Evidence for a Thick Disk of Dark Molecular Gas in the Outer Galaxy

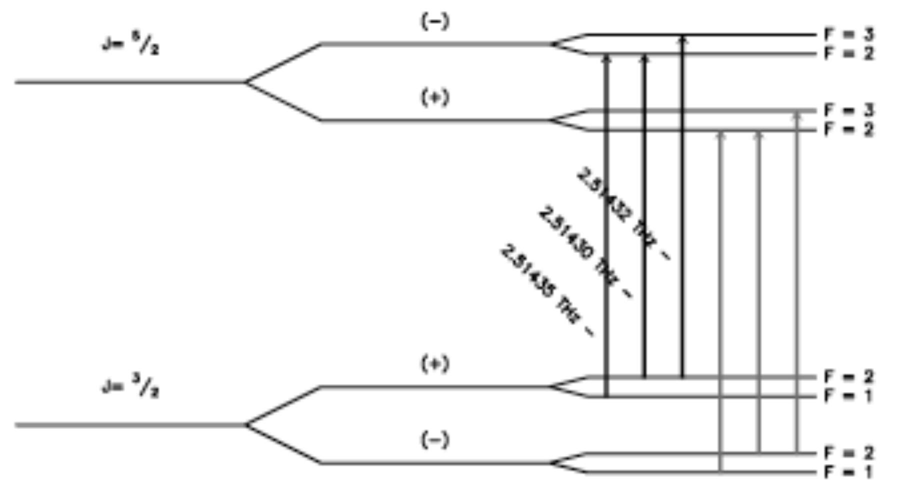
Michael P. Busch[1,5,6,7], Philip D. Engelke[1,2], Ronald J. Allen[1,3,8], and David E. Hogg[4]
[1] Department of Physics and Astronomy, Johns Hopkins University, 3400 North Charles Street, Baltimore, MD 21218, USA
[2] Frontier Technology Inc., 100 Cummings Center Suite 450G, Beverly, MA 01915, USA
[3] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
[4] National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA 22903, USA



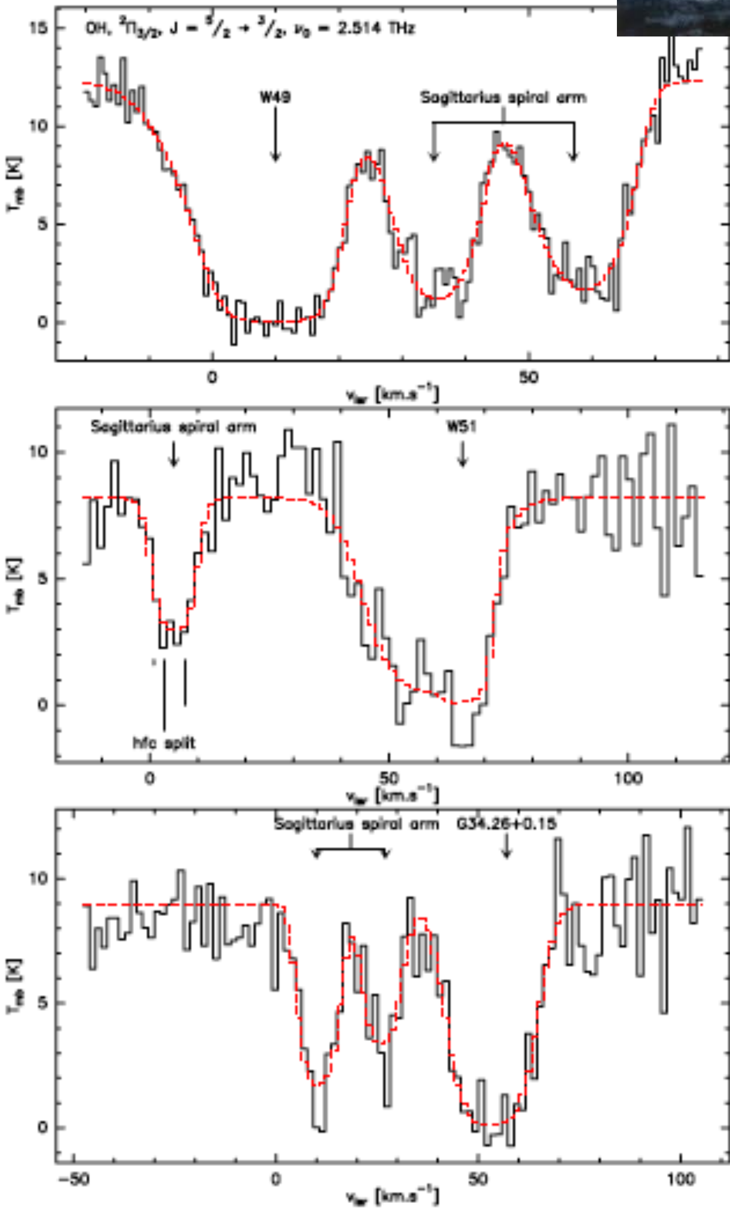
OH probes CO-dark molecular gas

Transition	Frequency [GHz][a]	A_E [s^{-1}][b]
OH, $^2\Pi_{3/2}, J = 5/2 \leftarrow 3/2$		
$F = 2^- \leftarrow 2^+$	2514.298092	0.0137
$F = 3^- \leftarrow 2^+$	2514.316386	0.1368
$F = 2^- \leftarrow 1^+$	2514.353165	0.1231
^{18}OH, $^2\Pi_{3/2}, J = 5/2 \leftarrow 3/2$		
$F = 2^+ \leftarrow 2^-$	2494.68092	0.0136
$F = 3^+ \leftarrow 2^-$	2494.69507	0.1356
$F = 2^+ \leftarrow 1^-$	2494.73421	0.1221





Wiesemeyer et al. 2012



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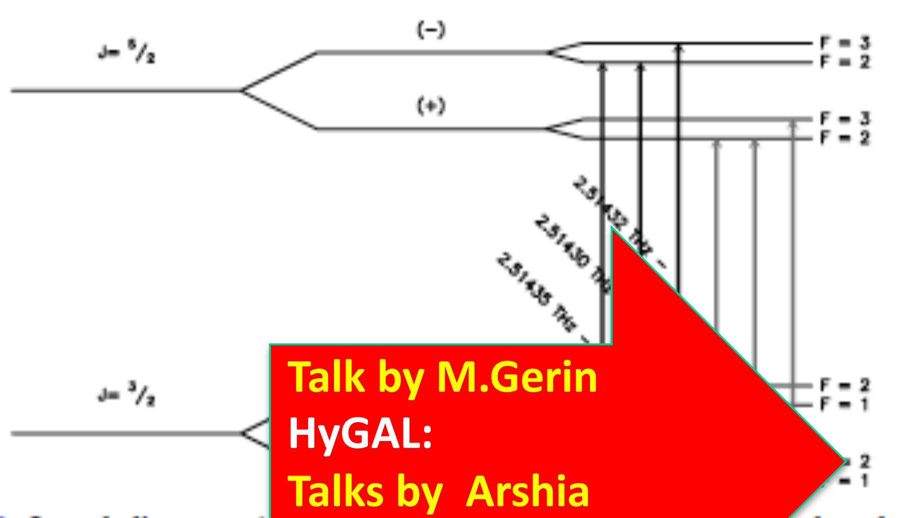
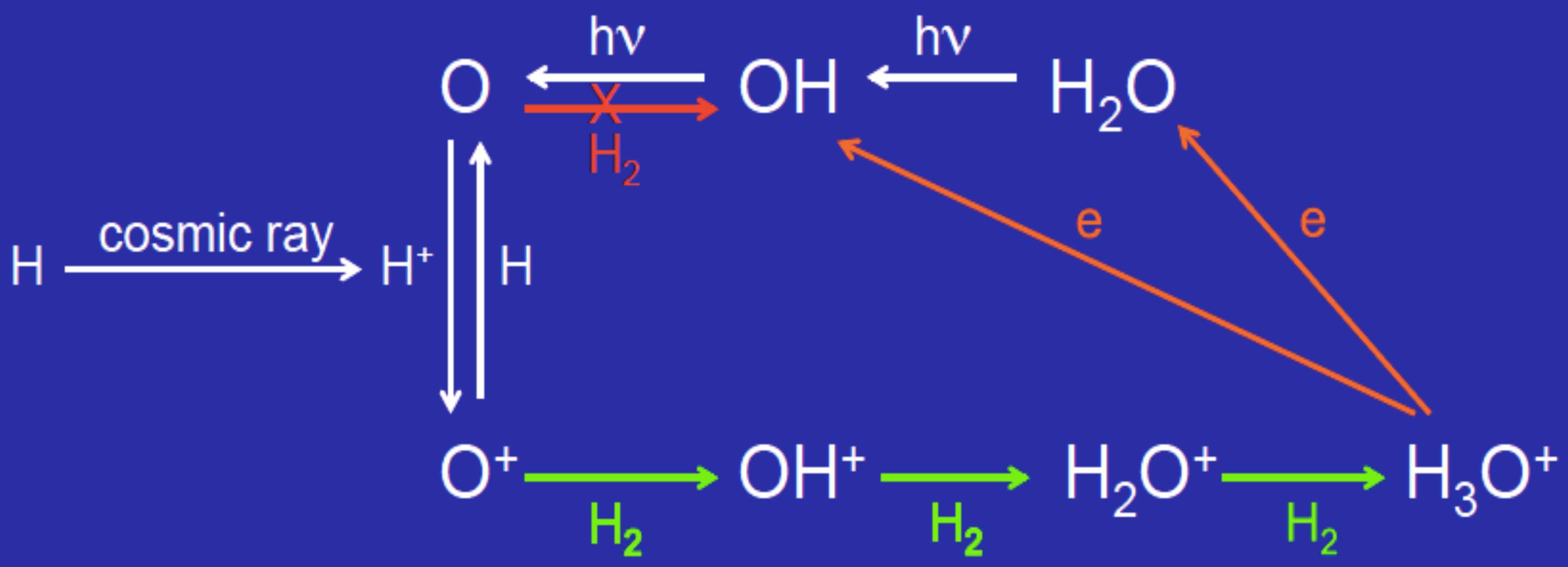


Talk by M.Gerin
HyGAL:
Talks by Arshia Jacob & Wonju Kim

Wiesemeyer et al. 2012

Chemistry of interstellar oxygen

- Chemistry is initiated by cosmic rays



D. Neufeld

Chemistry of interstellar oxygen

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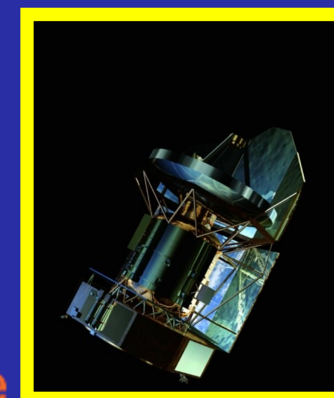


O ← OH ← H_2O (hν)

O → OH (H_2) X

$H \xrightarrow{\text{cosmic ray}} H^+$

$H^+ \rightleftarrows O^+$ (H)

$O^+ \xrightarrow{H_2} OH^+ \xrightarrow{H_2} H_2O^+ \xrightarrow{H_2} H_3O^+$

$H_3O^+ \xrightarrow{e} OH$, $H_3O^+ \xrightarrow{e} H_2O$

D. Neufeld

OBSERVATIONS OF A STRONG UNIDENTIFIED MICROWAVE LINE AND OF EMISSION FROM THE OH MOLECULE

By Prof. HAROLD WEAVER, Dr. DAVID R. W. WILLIAMS, Dr. N. H. DIETER and W. T. LUM
Radio Astronomy Laboratory, University of California, Berkeley

Nature 1965

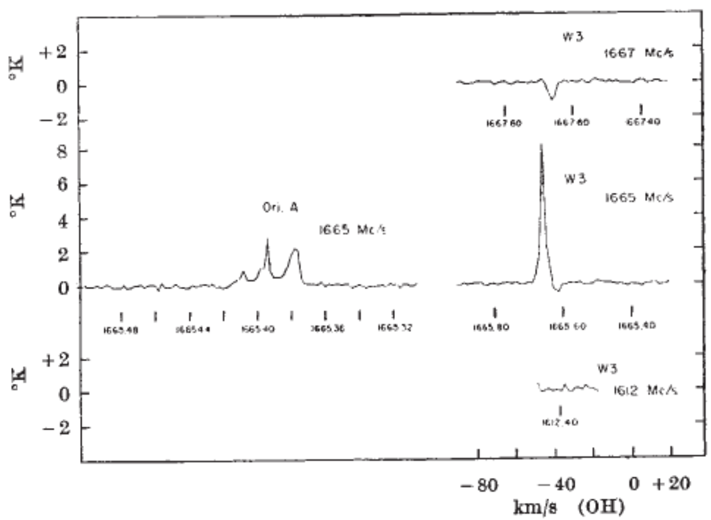


Fig. 1. Spectra of Ori *A* and *W*3 with a resolution of 10 kc/s (1·8 km/sec).

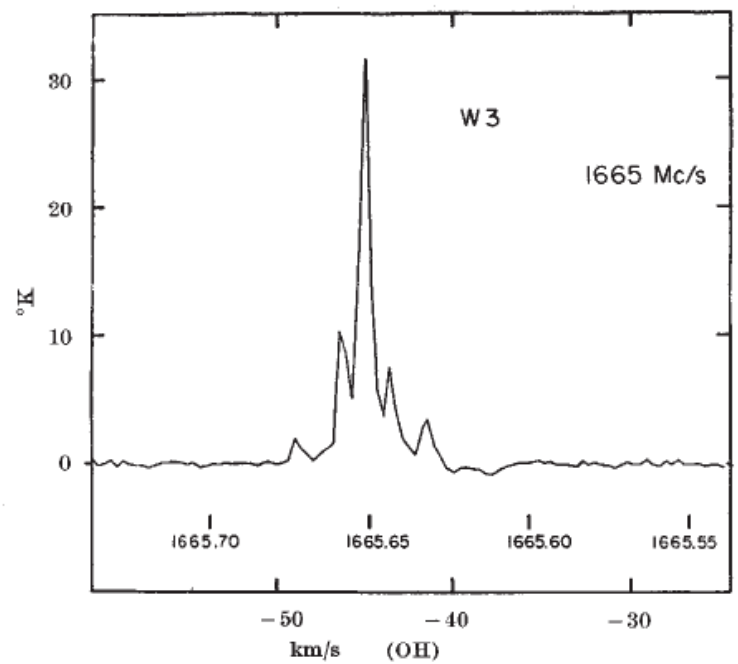
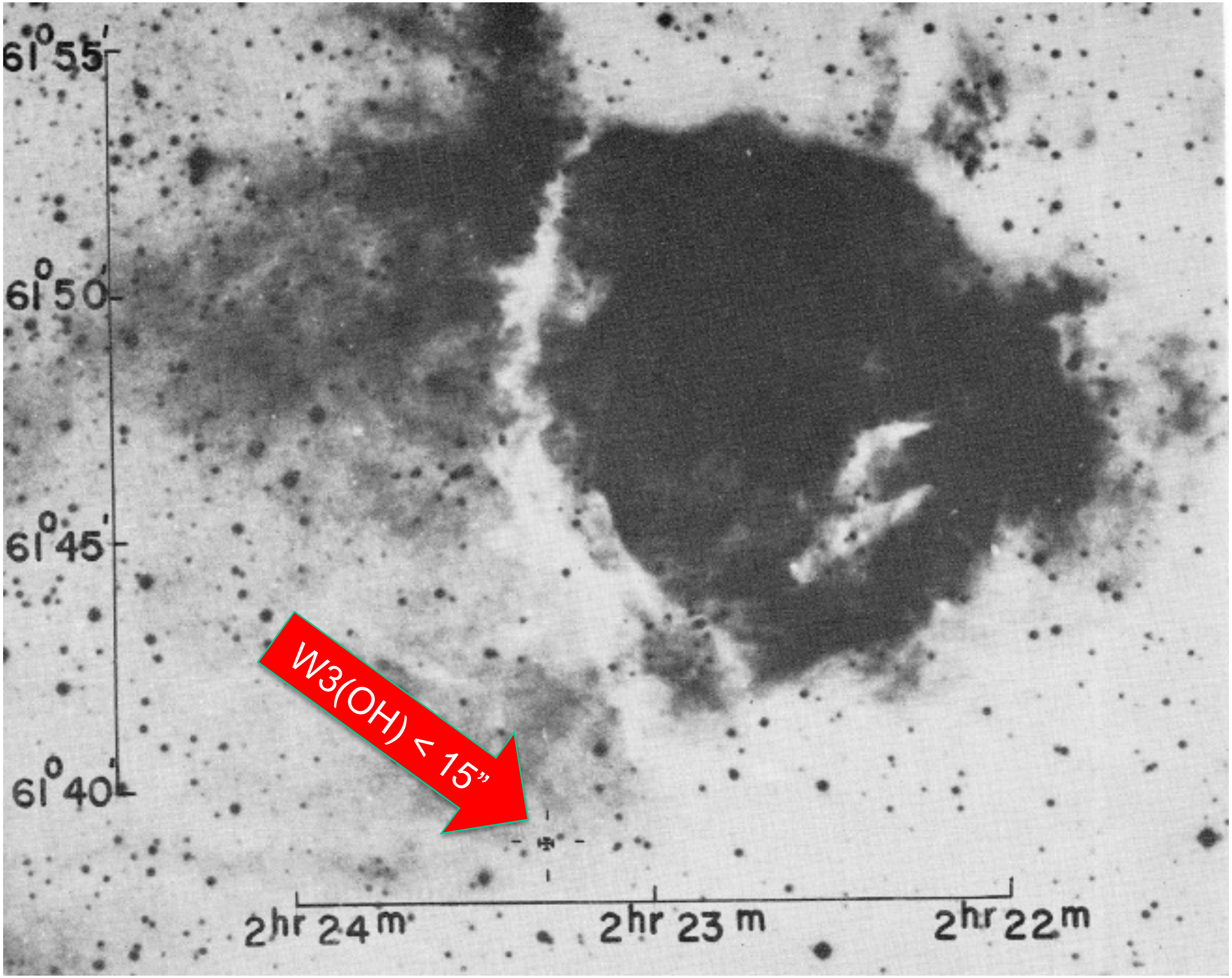


Fig. 2. Spectrum of *W*3 at 1,665 Mc/s with a resolution of 2 kc/s (0·4 km/sec)

MYSTERIUM



Early VLBI

Rogers+ 1967, ApJ
& Rogers+ 1966, Phys. Rev. Letters

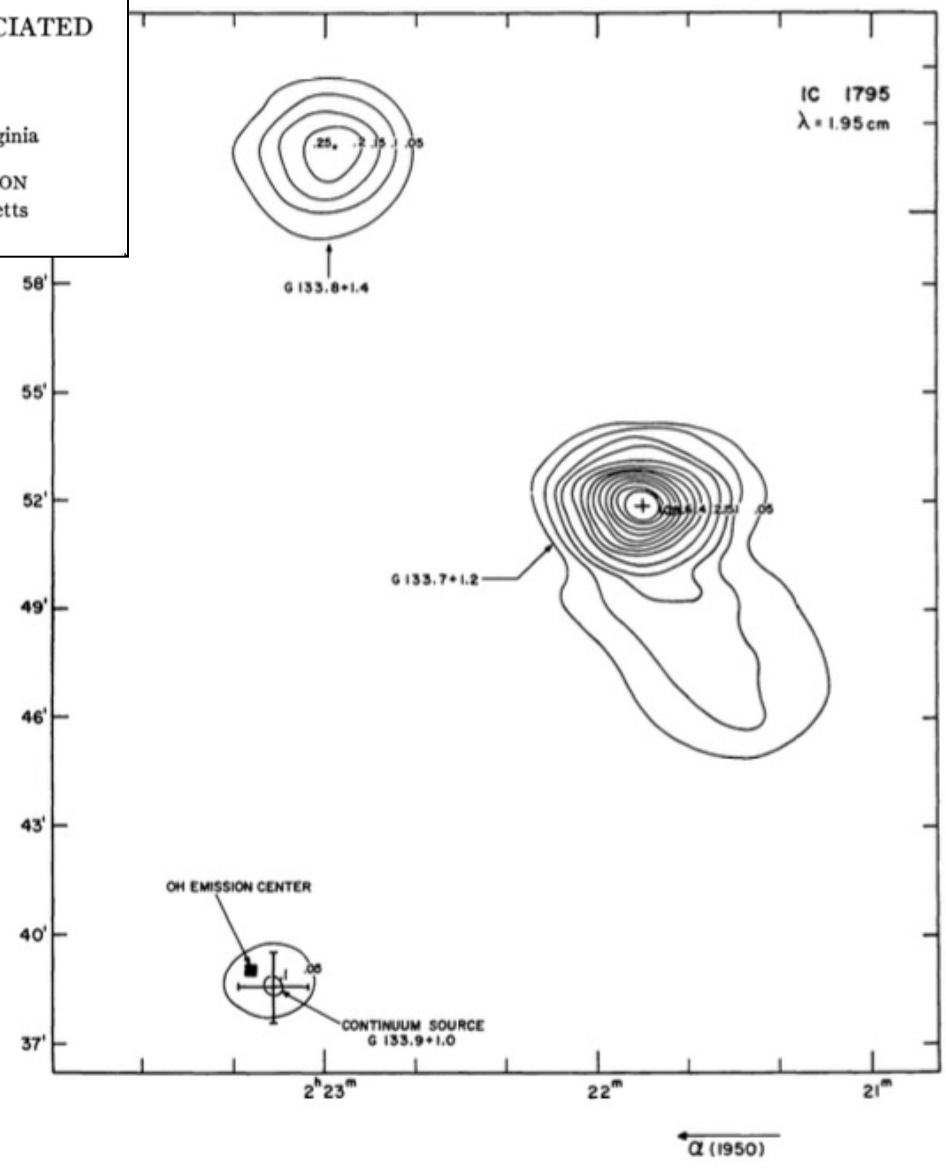
The Astrophysical Journal, Vol. 150, December 1967

A NEW CLASS OF COMPACT H II REGIONS ASSOCIATED WITH OH EMISSION SOURCES

P. G. Mezger, W. Altenhoff, J. Schraml
National Radio Astronomy Observatory,* Green Bank, West Virginia

B. F. Burke, E. C. Reifenstein III, and T. L. Wilson
Massachusetts Institute of Technology,† Cambridge, Massachusetts

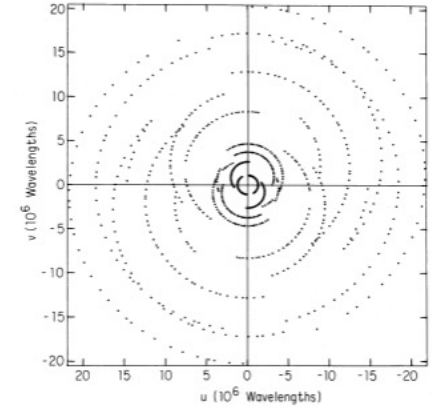
Received September 26, 1967

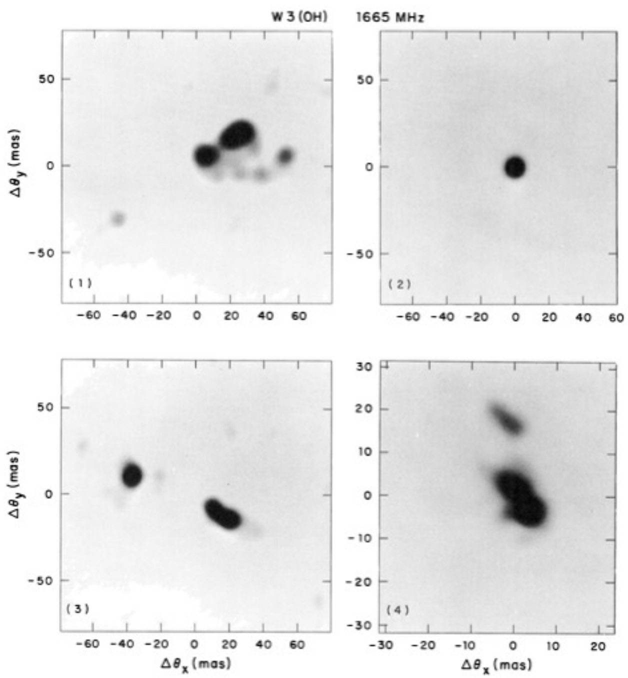


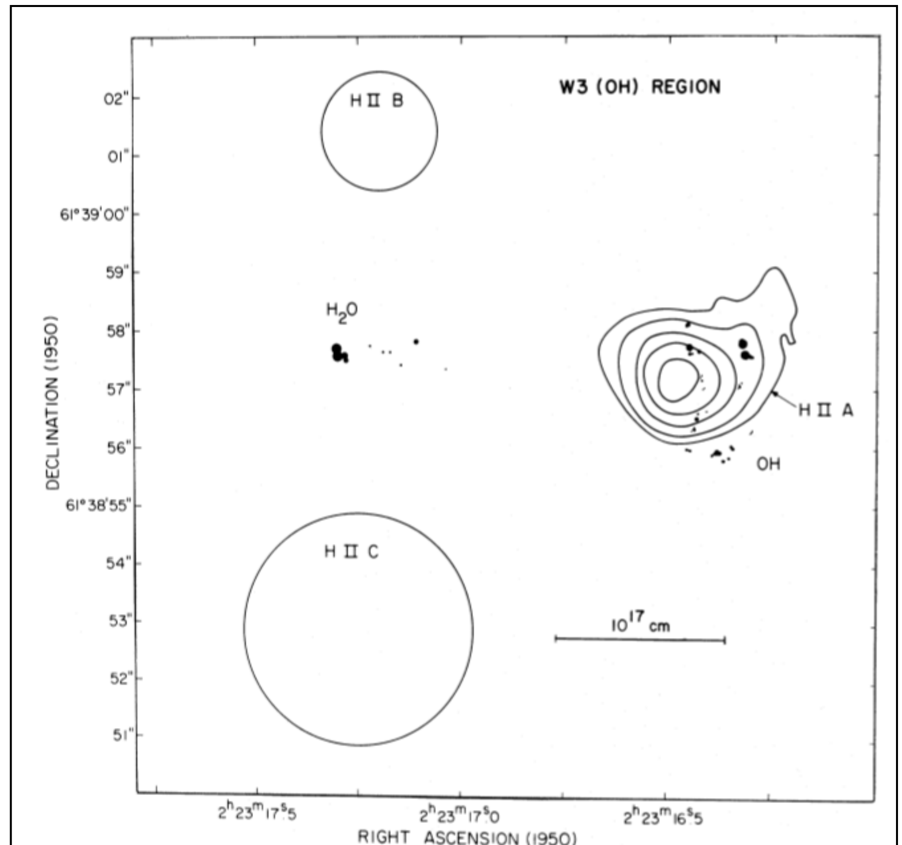
THE ASTROPHYSICAL JOURNAL, 239:89–111, 1980 July 1

THE STRUCTURE OF INTERSTELLAR HYDROXYL MASERS: VLBI SYNTHESIS OBSERVATIONS OF W3(OH)

M. J. REID
Harvard-Smithsonian Center for Astrophysics; and National Radio Astronomy Observatory[1]
A. D. HASCHICK AND B. F. BURKE
Research Laboratory of Electronics, Massachusetts Institute of Technology
J. M. MORAN
Harvard-Smithsonian Center for Astrophysics
K. J. JOHNSTON
E. O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, D.C.
AND
G. W. SWENSON, JR.
Vermilion River Observatory, University of Illinois
Received 1979 October 22; accepted 1979 December 27

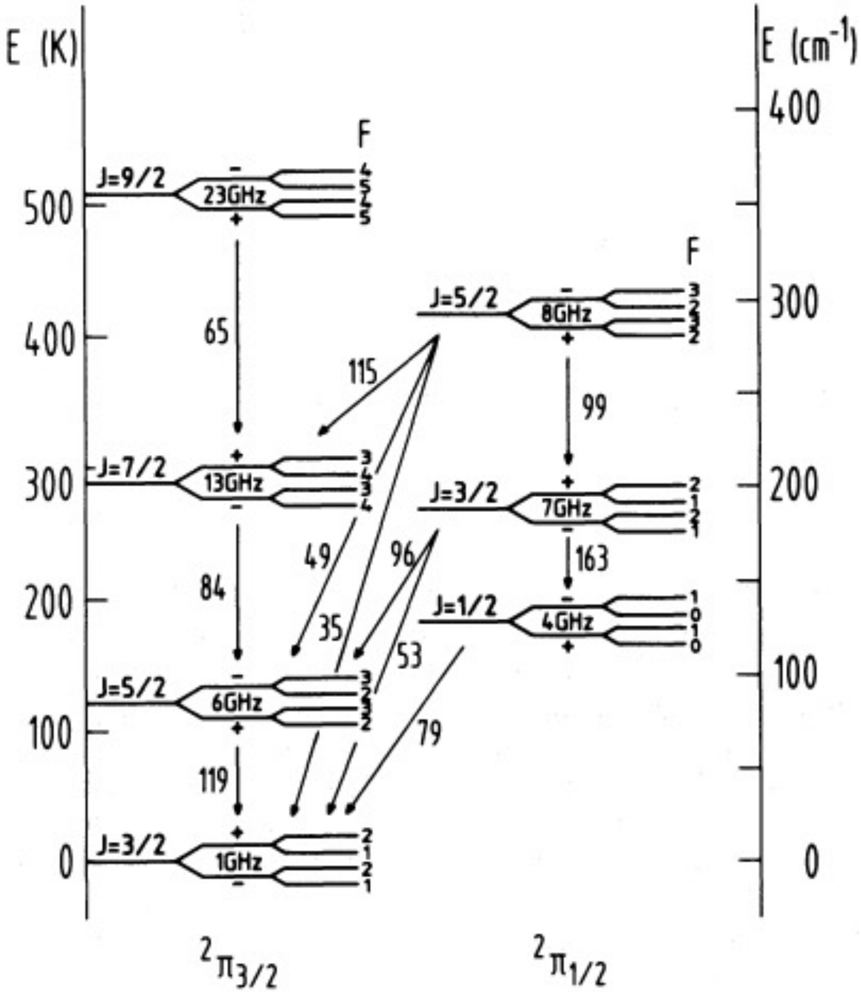




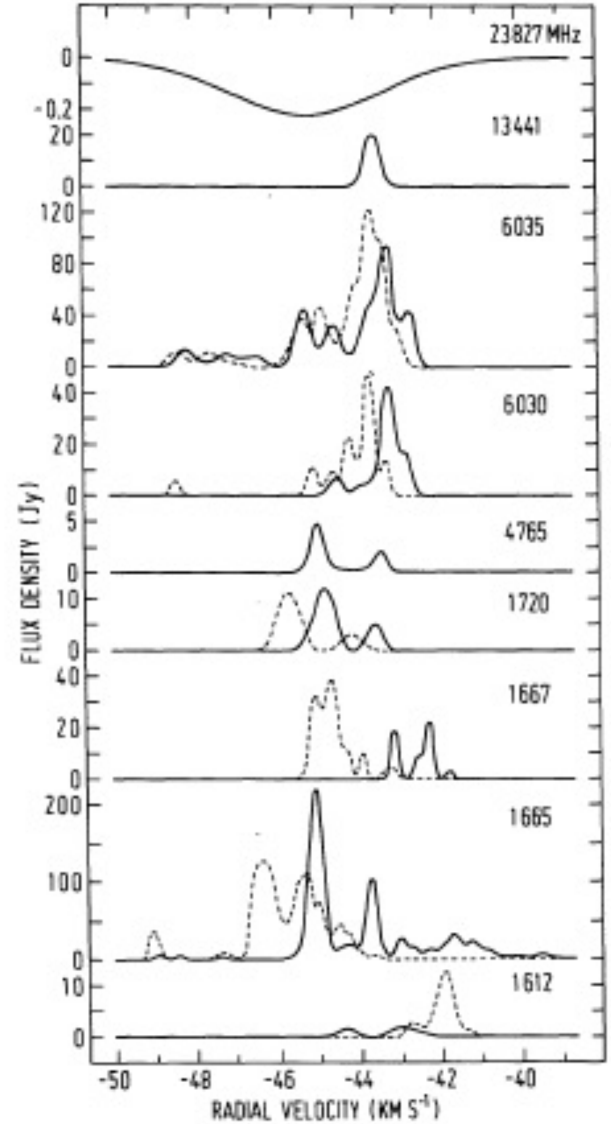


Reid+ 1980

Hydroxyl radio maser emission and absorption:

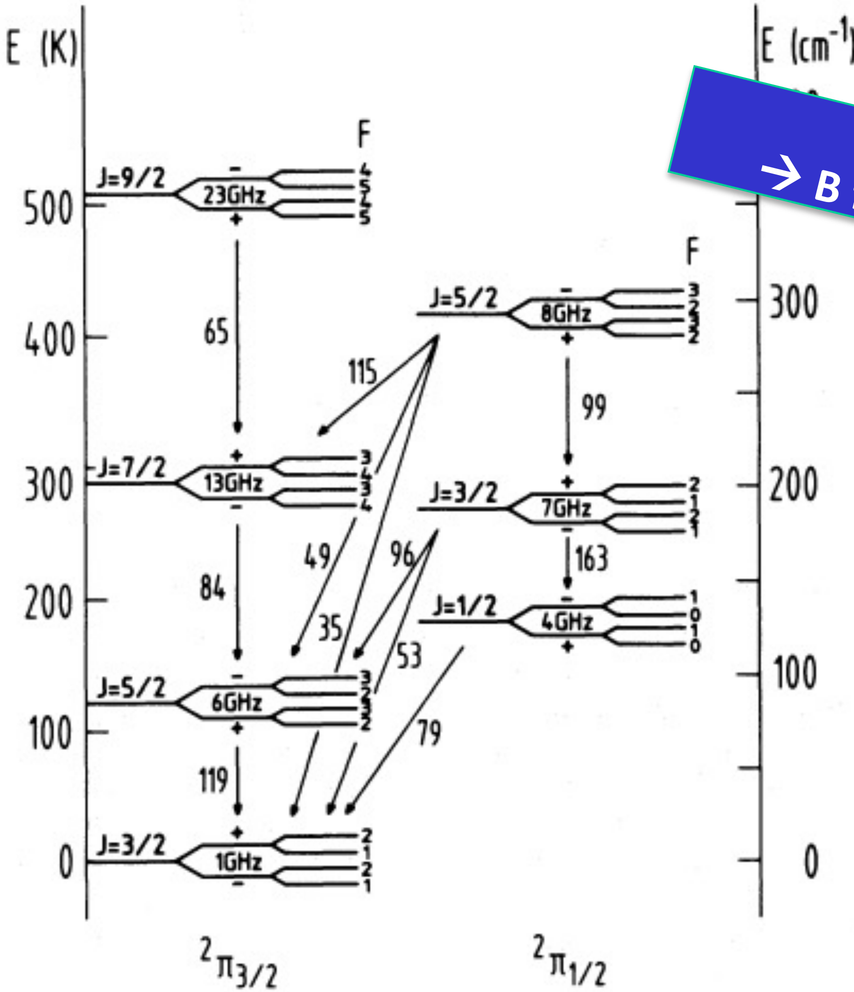


W3(OH)

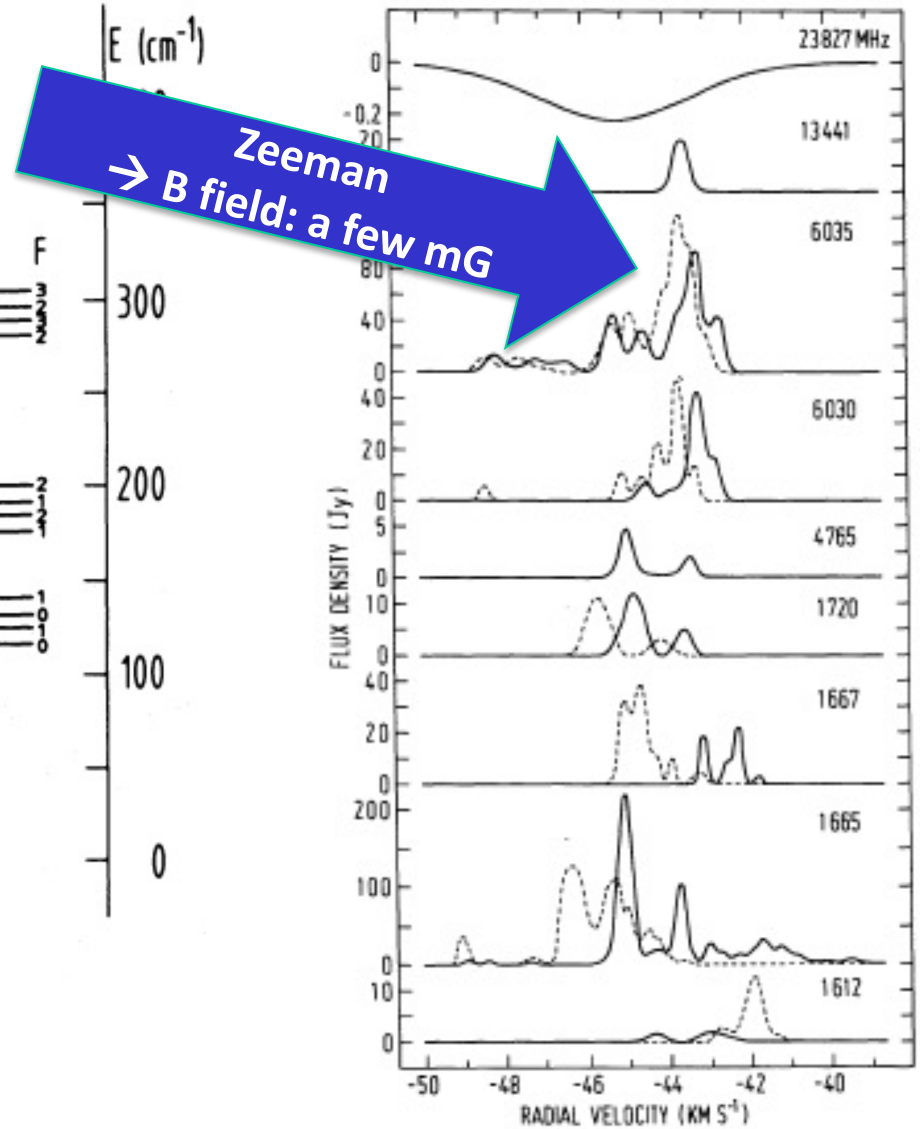


Baudry, Guilloteau, Walmsley, Wilson, Winnberg, …

Hydroxyl radio maser emission and absorption:



W3(OH)



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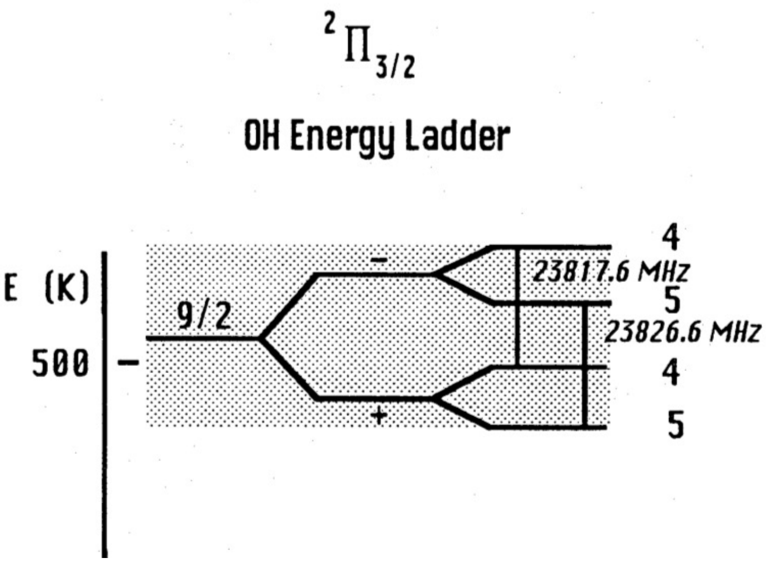
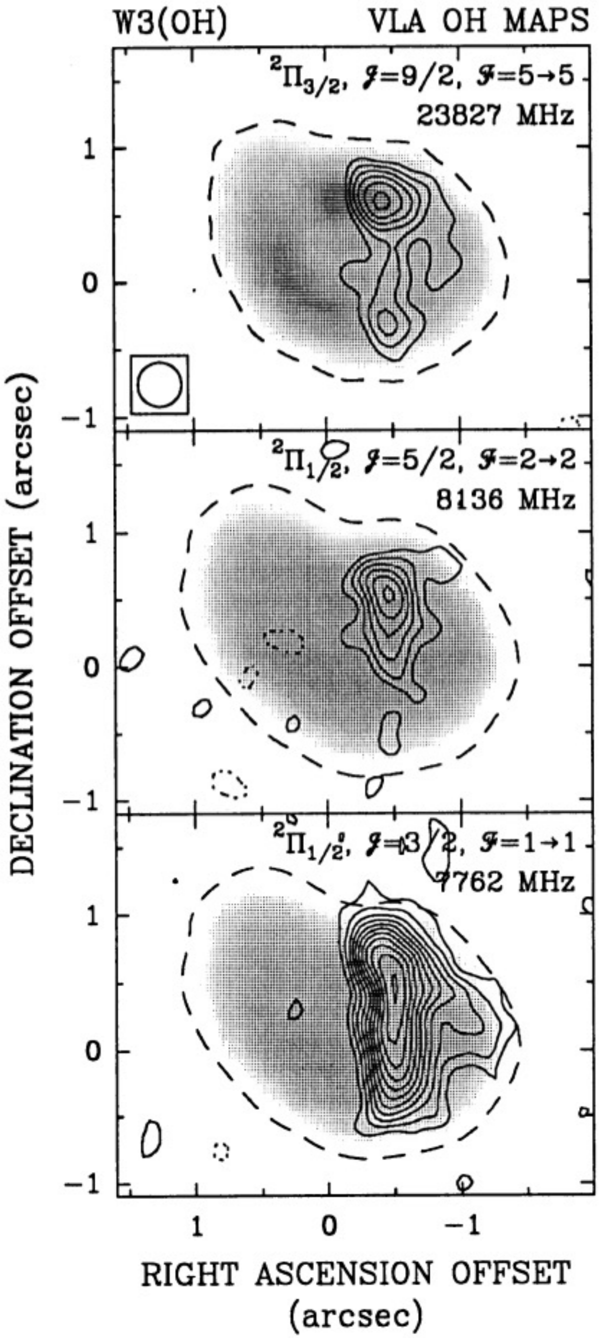
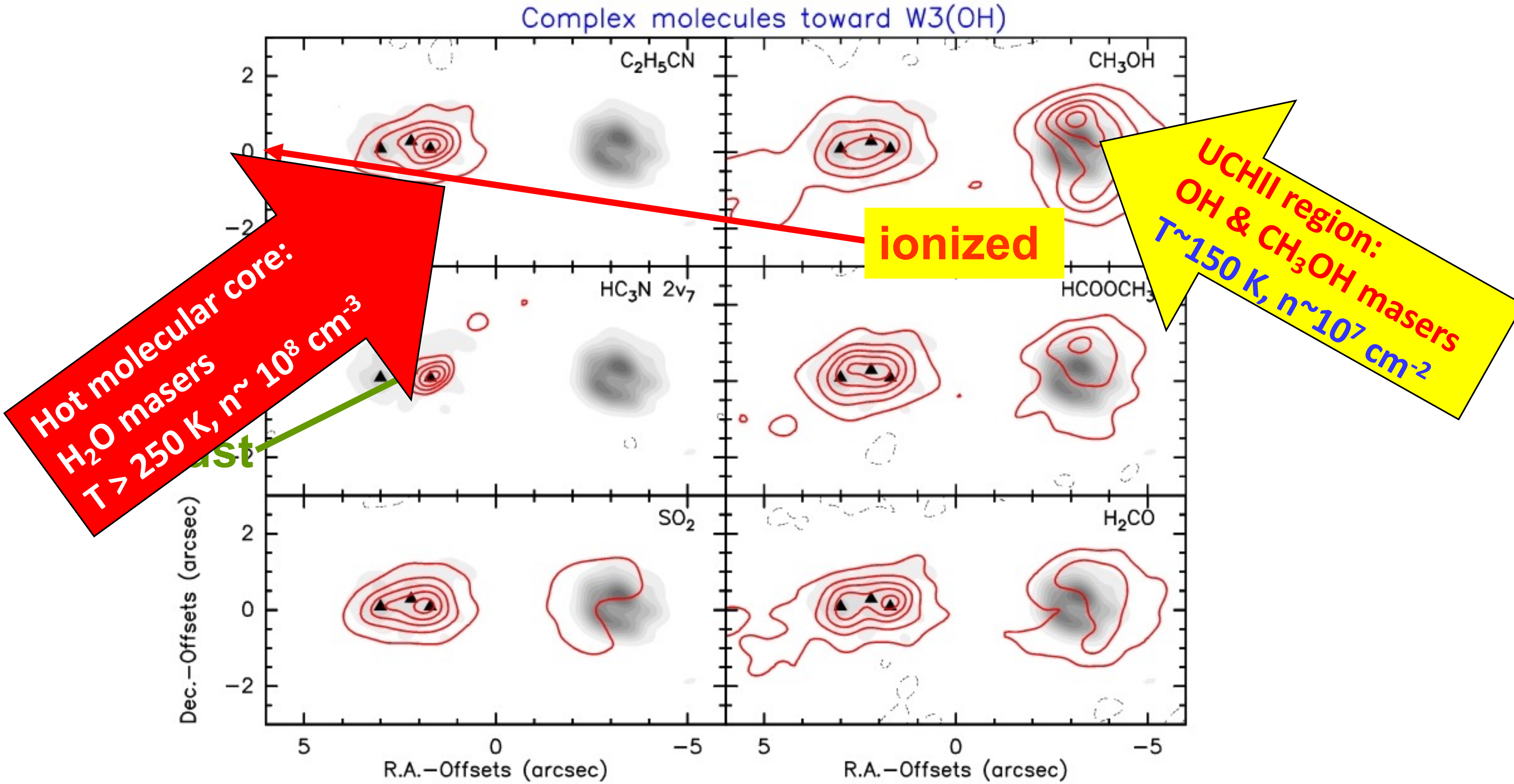


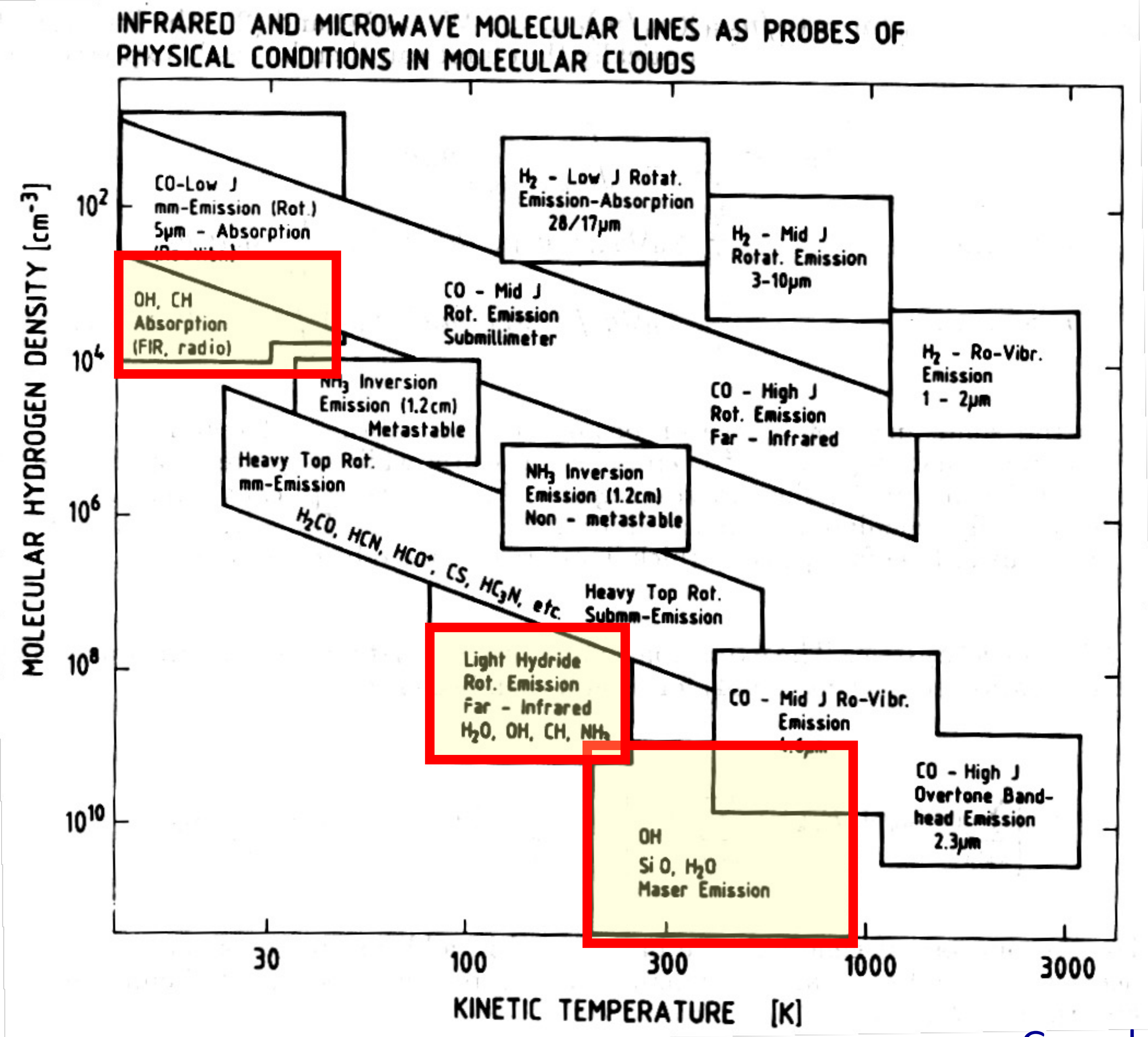


Baudry & Menten (1995)

Chemical (and evolutionary) diversity in the W3(OH) region

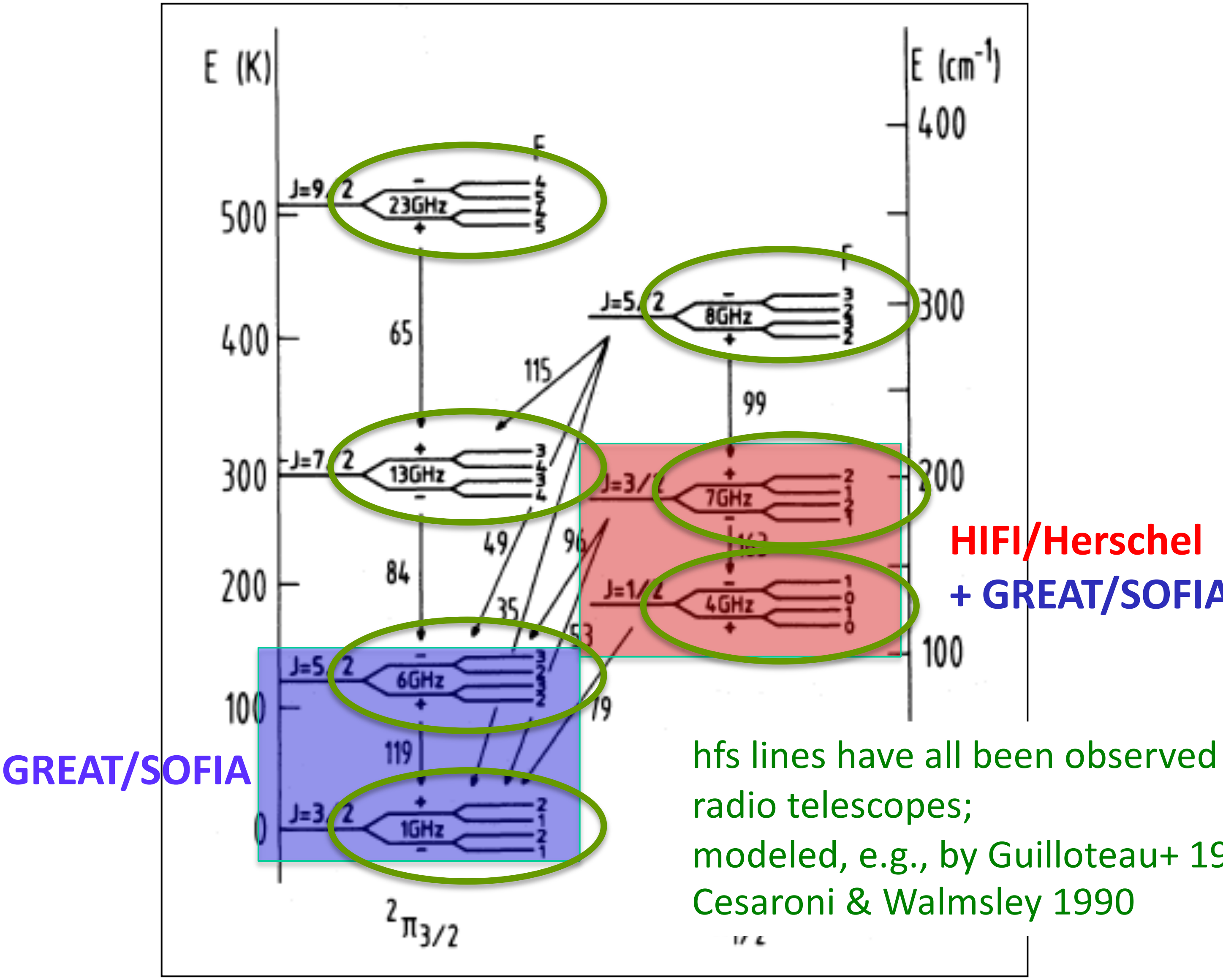


Wyrowski et al. 1999


INFRARED AND MICROWAVE MOLECULAR LINES AS PROBES OF PHYSICAL CONDITIONS IN MOLECULAR CLOUDS
MOLECULAR HYDROGEN DENSITY [cm^{-3}]
10^2
10^4
10^6
10^8
10^{10}
KINETIC TEMPERATURE [K]
30
100
300
1000
3000
CO-Low J mm-Emission (Rot.) 5μm - Absorption
OH, CH Absorption (FIR, radio)
H_2 - Low J Rotat. Emission-Absorption 28/17μm
H_2 - Mid J Rotat. Emission 3-10μm
CO - Mid J Rot. Emission Submillimeter
H_2 - Ro-Vibr. Emission 1 - 2μm
NH_3 Inversion Emission (1.2cm) Metastable
CO - High J Rot. Emission Far - Infrared
Heavy Top Rot. mm-Emission
NH_3 Inversion Emission (1.2cm) Non - metastable
H_2CO, HCN, HCO^+, CS, HC_3N, etc.
Heavy Top Rot. Submm-Emission
Light Hydride Rot. Emission Far - Infrared H_2O, OH, CH, NH_3
CO - Mid J Ro-Vibr. Emission
CO - High J Overtone Band-head Emission 2.3μm
OH SiO, H_2O Maser Emission

Genzel 1988

OH Energy Levels



hfs lines have all been observed with radio telescopes;
modeled, e.g., by Guilloteau+ 1981, Cesaroni & Walmsley 1990

Transition	Frequency [GHz][a]	A_E [s^{-1}][b]
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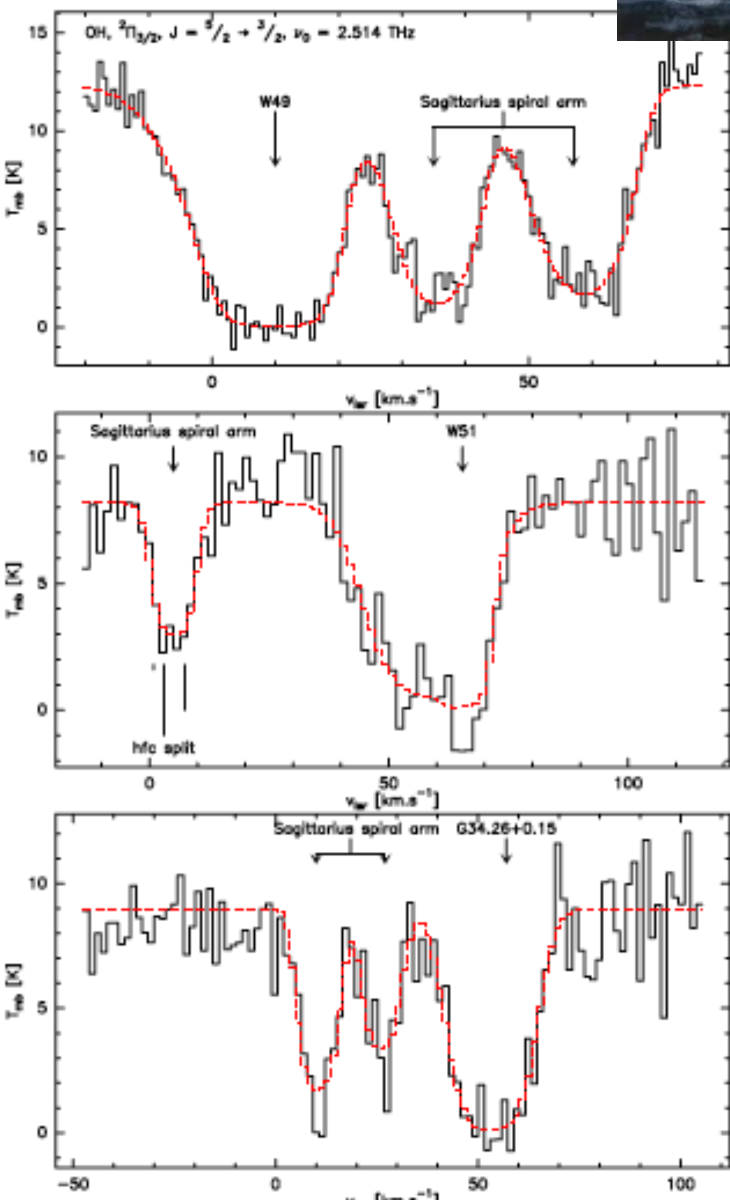
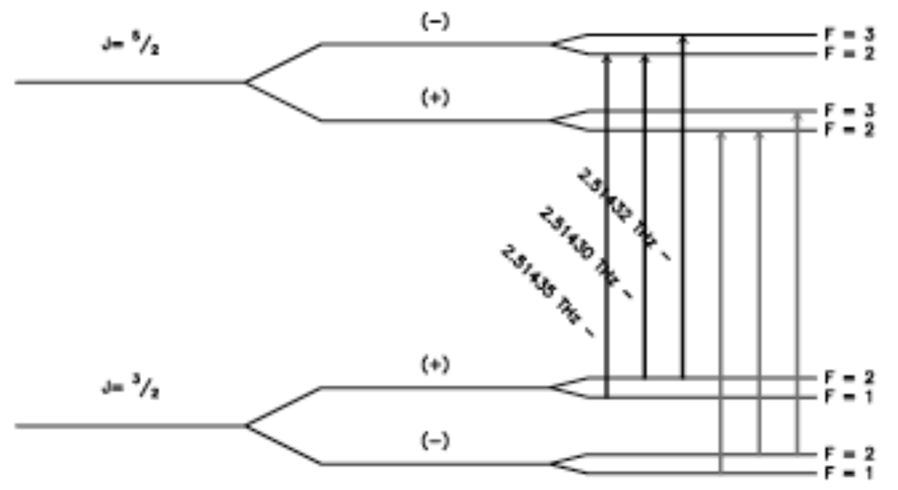
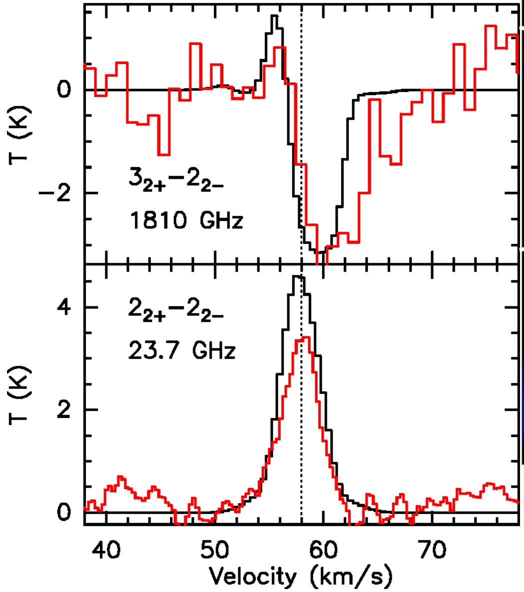
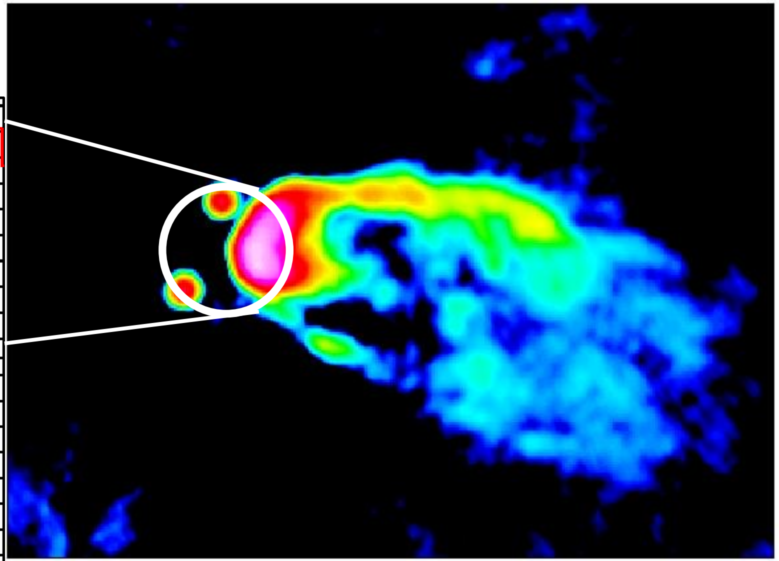




Wiesemeyer et al. 2012

Ammonia/1.8 THz: Probing infall

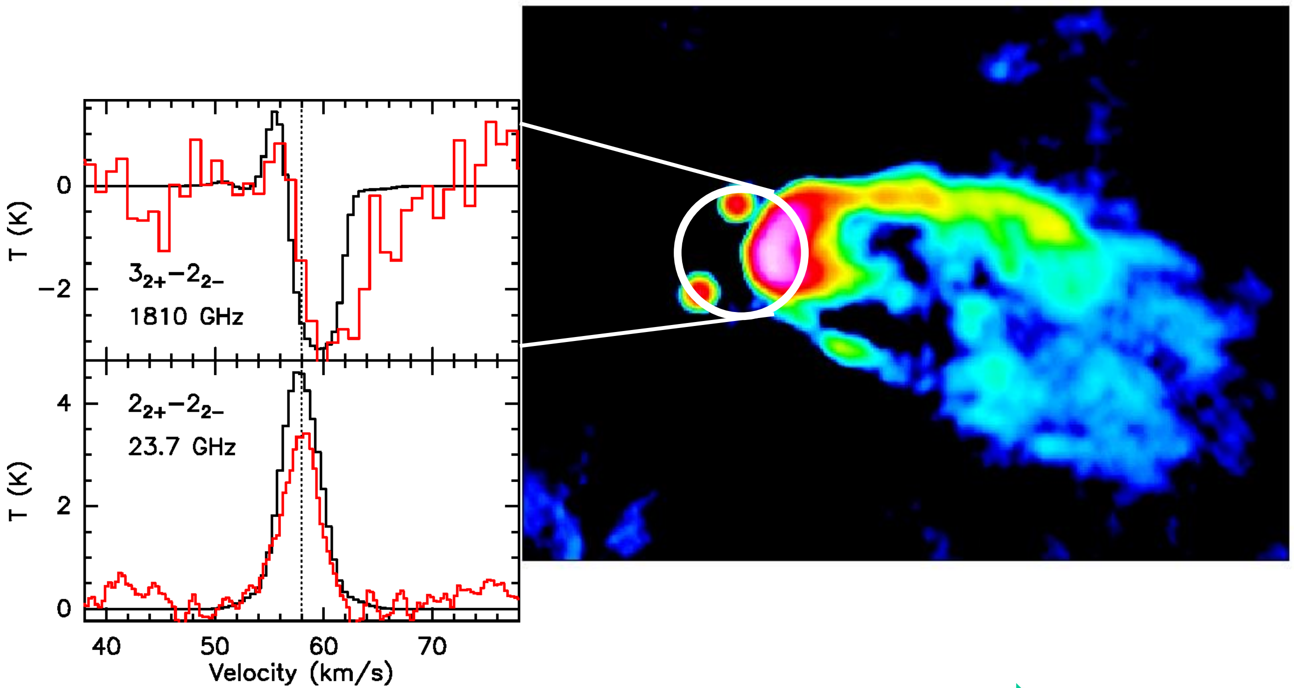




→ Mass infall rates:
a few x 10^{-3} $M_{\odot}$/yr

Wyrowski + 2012, 2016
See also Hajigholi+ 2016 (Herschel/HIFI)

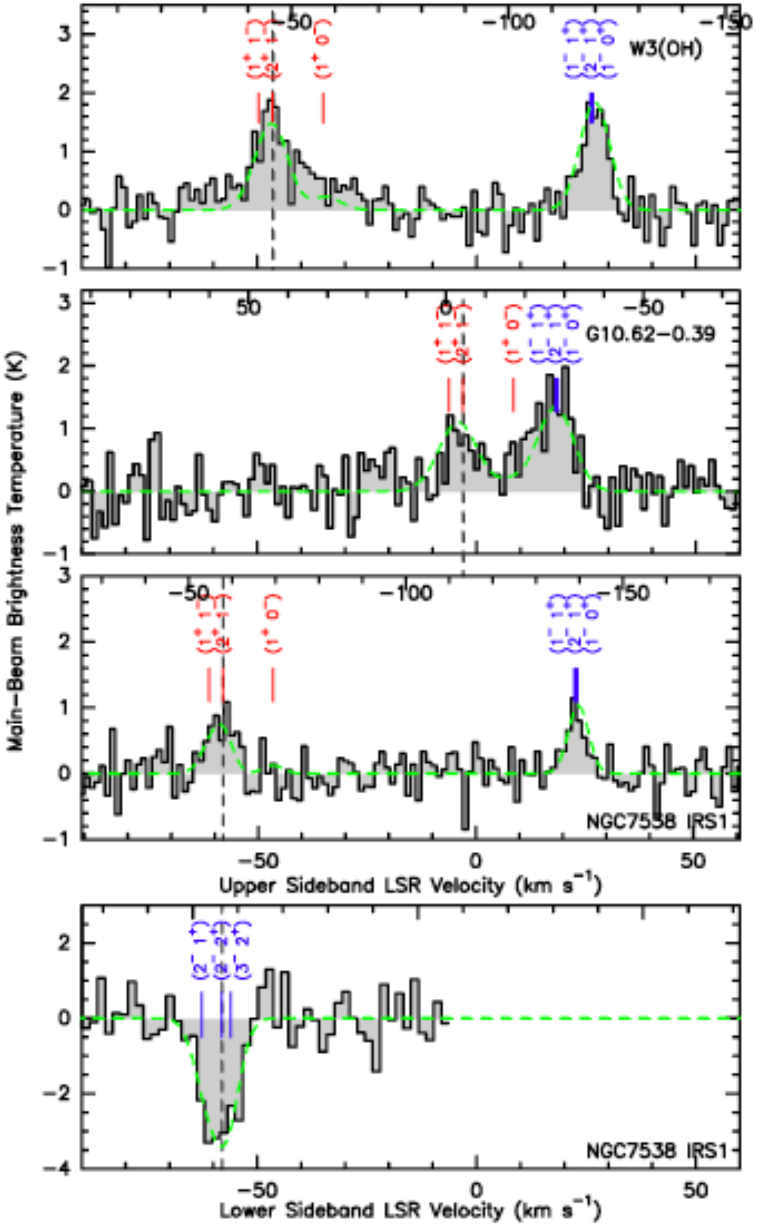
Ammonia/1.8 THz: Probing infall

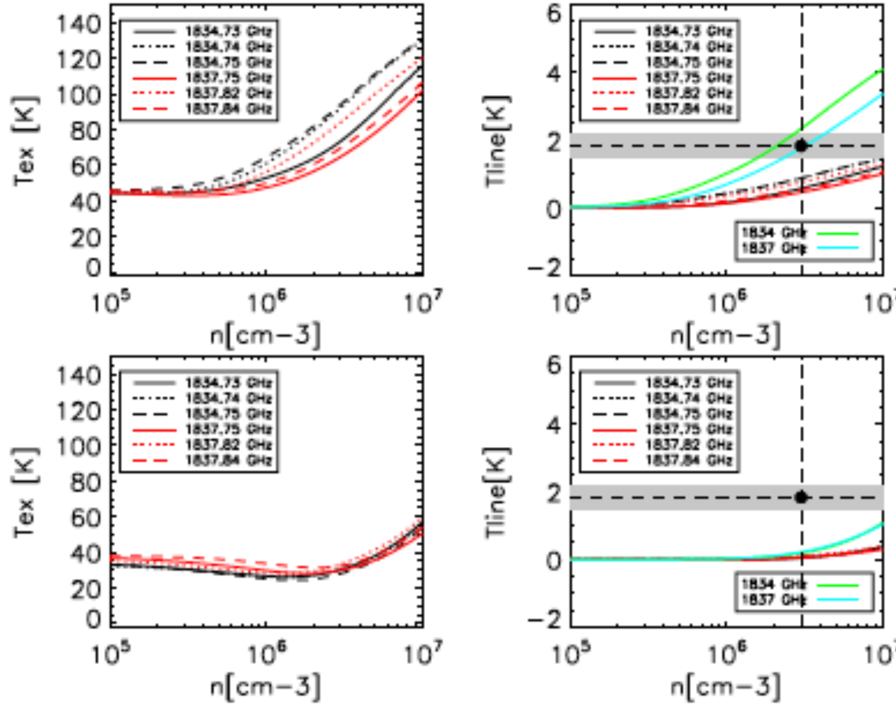


→ Mass infall rates: a few x 10^{-3} $M_\odot$/yr

Talk by F. Wyrowski

Wyrowski + 2012, 2016
See also Hajigholi+ 2016 (Herschel/HIFI)





LVG Modeling

- Combining radio hfs and FIR rotational line information

A&A 542, L8 (2012)
DOI: 10.1051/0004-6361/201218933

Astronomy & Astrophysics
Special feature

GREAT: early science results

Letter to the Editor

SOFIA observations of far-infrared hydroxyl emission toward classical ultracompact HII/OH maser regions★

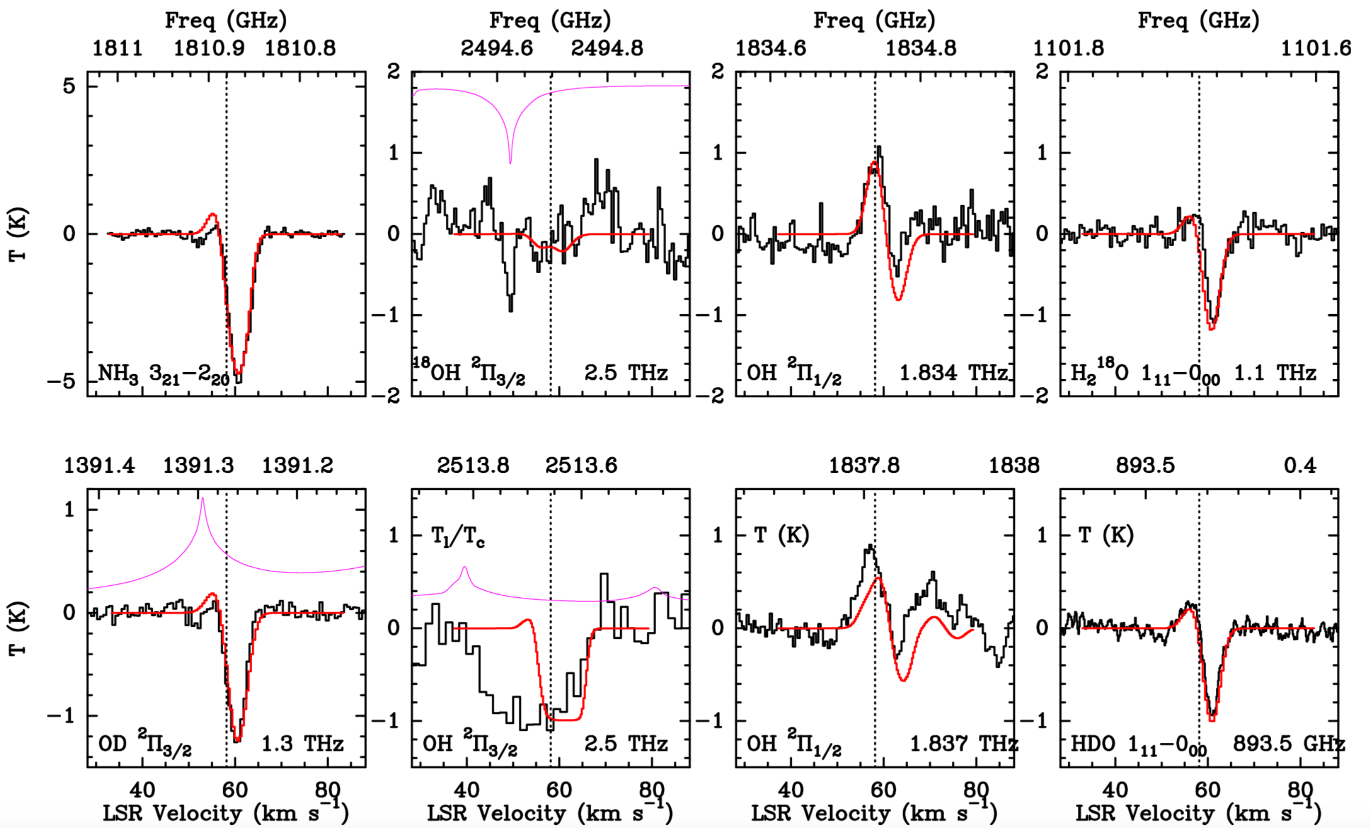
T. Csengeri[1], K. M. Menten[1], F. Wyrowski[1], M. A. Requena-Torres[1], R. Güsten[1], H. Wiesemeyer[1], H.-W. Hübers[2,3], P. Hartogh[4], and K. Jacobs[5]

A&A 658, A193 (2022)
https://doi.org/10.1051/0004-6361/202140577

Astronomy & Astrophysics

SOFIA/GREAT observations of OD and OH rotational lines towards high-mass star forming regions

T. Csengeri[1,2], F. Wyrowski[2], K. M. Menten[2], H. Wiesemeyer[2], R. Güsten[2], J. Stutzki[3], S. Heyminck[2], and Y. Okada[3]



G34.25+0.15

Astron. Astrophys. 67, 323—332 (1978)

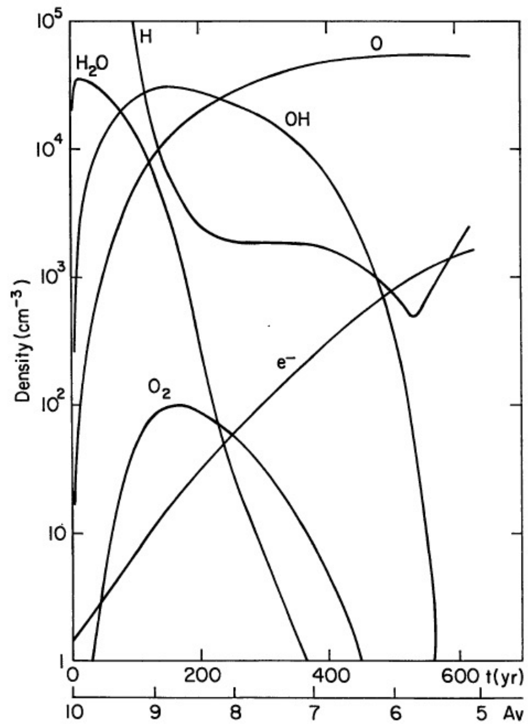
ASTRONOMY AND ASTROPHYSICS

A Model for the Maser Sources Associated with H II Regions

M. Elitzur*[1] and T. de Jong[2]

[1] Departments of Physics and Astronomy, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA
[2] Astronomical Institute, University of Amsterdam, Amsterdam, The Netherlands

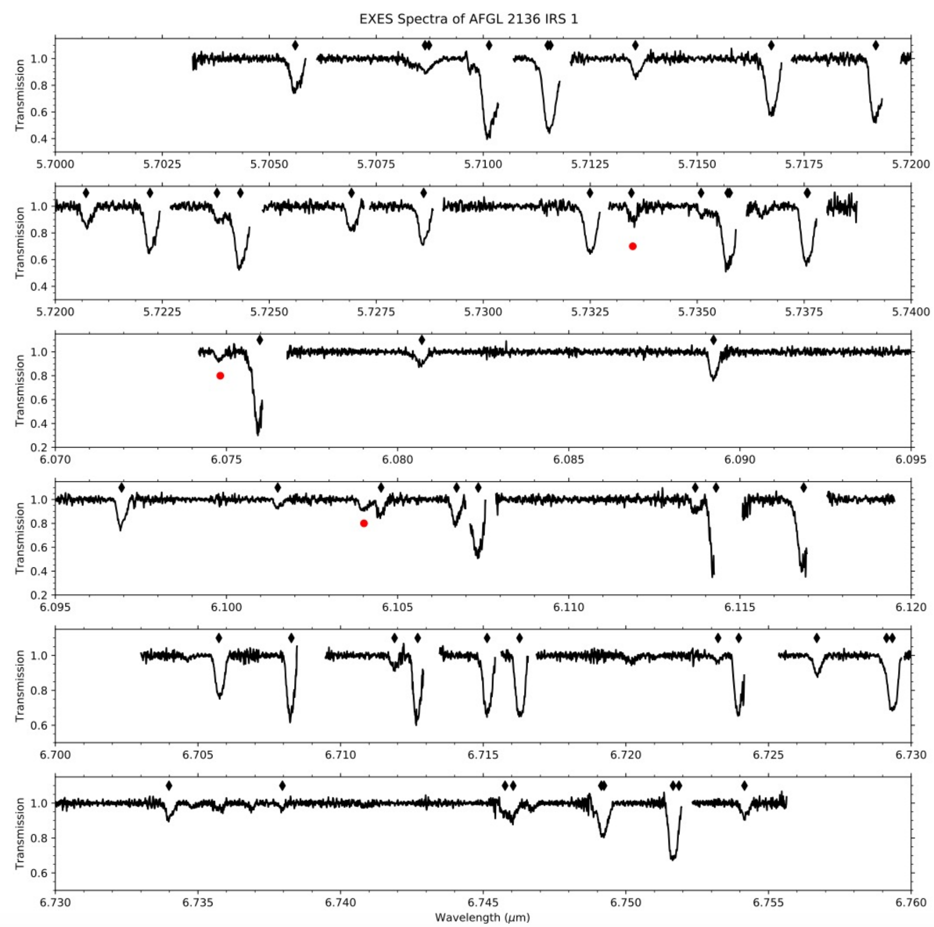
- H_2O formed in shock front
- Gets dissociated to OH in ionization front
- OH masers are pumped by FIR radiation from warm dust

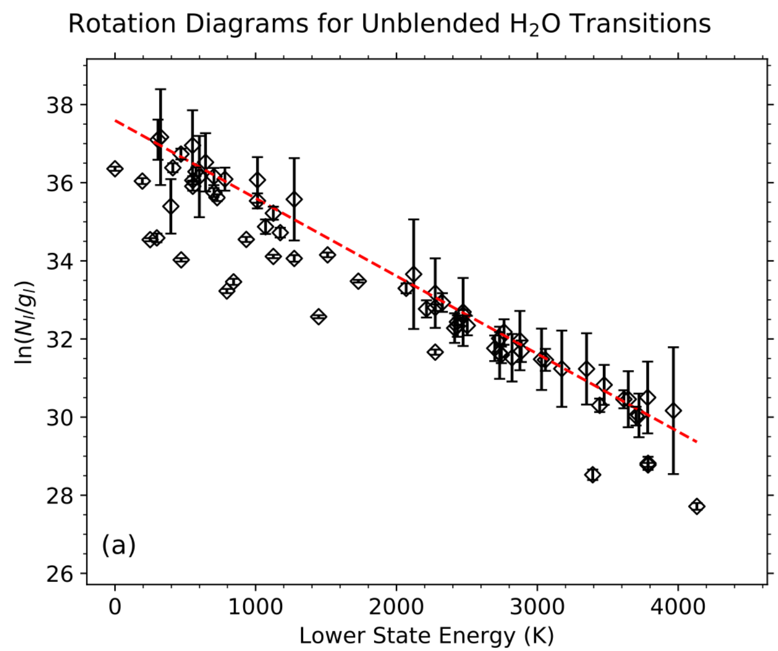


The Astrophysical Journal, 894:107 (21pp), 2020 May 10
https://doi.org/10.3847/1538-4357/ab88a1

The H_2O Spectrum of the Massive Protostar AFGL 2136 IRS 1 from 2 to 13 μm at High Resolution: Probing the Circumstellar Disk

Nick Indriolo[1], D. A. Neufeld[2], A. G. Barr[3], A. C. A. Boogert[4], C. N. DeWitt[5], A. Karska[6], E. J. Montiel[5], M. J. Richter[7], and A. G. G. M. Tielens[3]





T_{rot} (H_2O) = 519 K

H_2O and $H_2{}^{18}O$ lines (SOFIA/EXES)

The Astrophysical Journal, 894:107 (21pp), 2020 May 10
https://doi.org/10.3847/1538-4357/ab88a1

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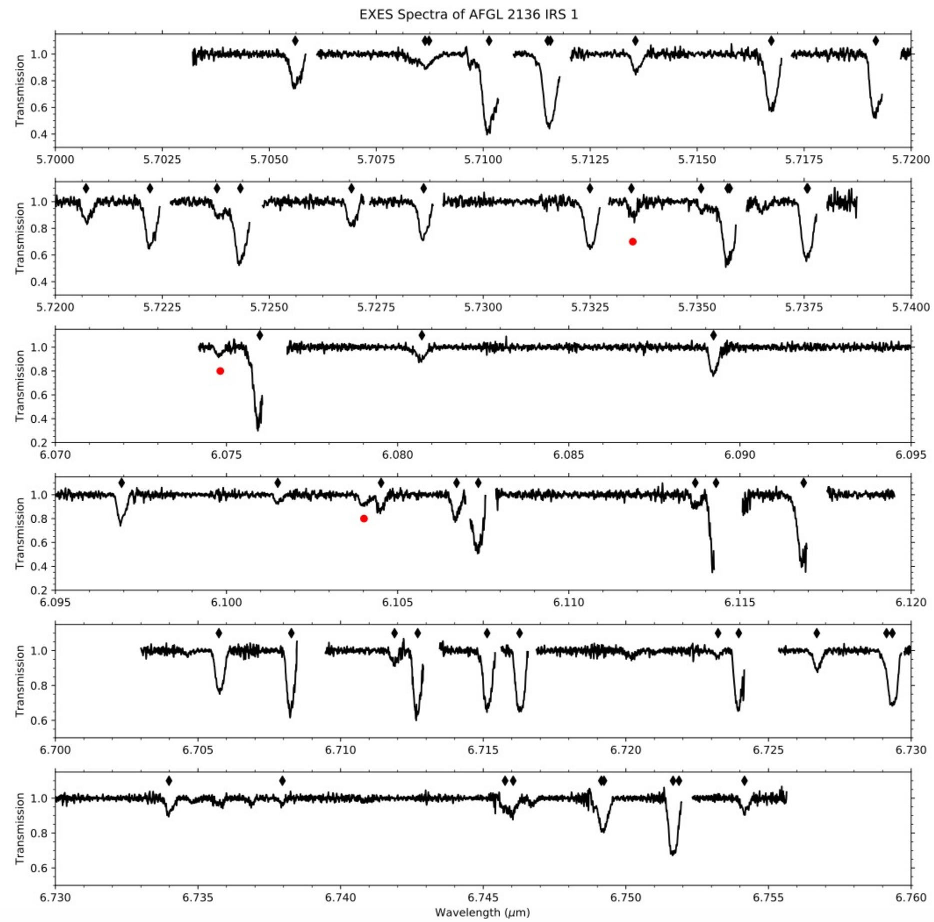
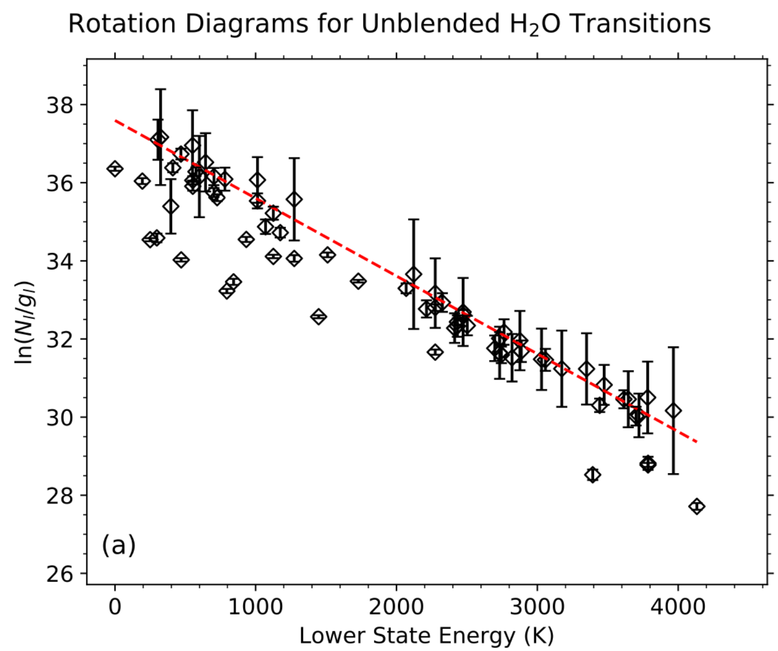




T_{rot} (H_2O) = 519 K

Talk by Jialu Li

H_2O and $H_2{}^{18}O$ lines (SOFIA/EXES)

Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS **493,** 3491–3495 (2020)
Advance Access publication 2020 February 24
doi:10.1093/mnras/staa530

The excitation of OH by H_2 revisited – II. Hyperfine resolved rate coefficients

J. Kłos,[1] P. J. Dagdigian,[2] M. H. Alexander,[1] A. Faure[3] and F. Lique[1,4]★

OH – H_2

Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

Royal Astronomical Society

MNRAS **518,** 5976–5981 (2023)
Advance Access publication 2022 November 25
https://doi.org/10.1093/mnras/stac3458

Collisional excitation of hyperfine levels of OH by hydrogen atoms

Paul J. Dagdigian★
Department of Chemistry, The Johns Hopkins University, Baltimore, MD 21218-2685, USA

OH – H

NATURE VOL. 246 DECEMBER 21/28 1973

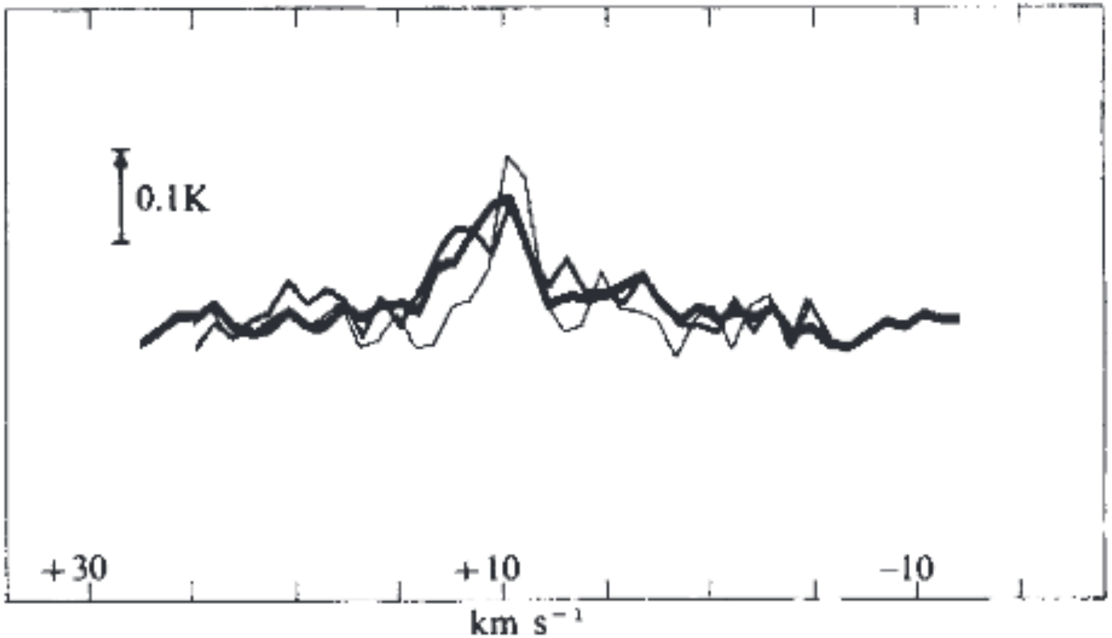
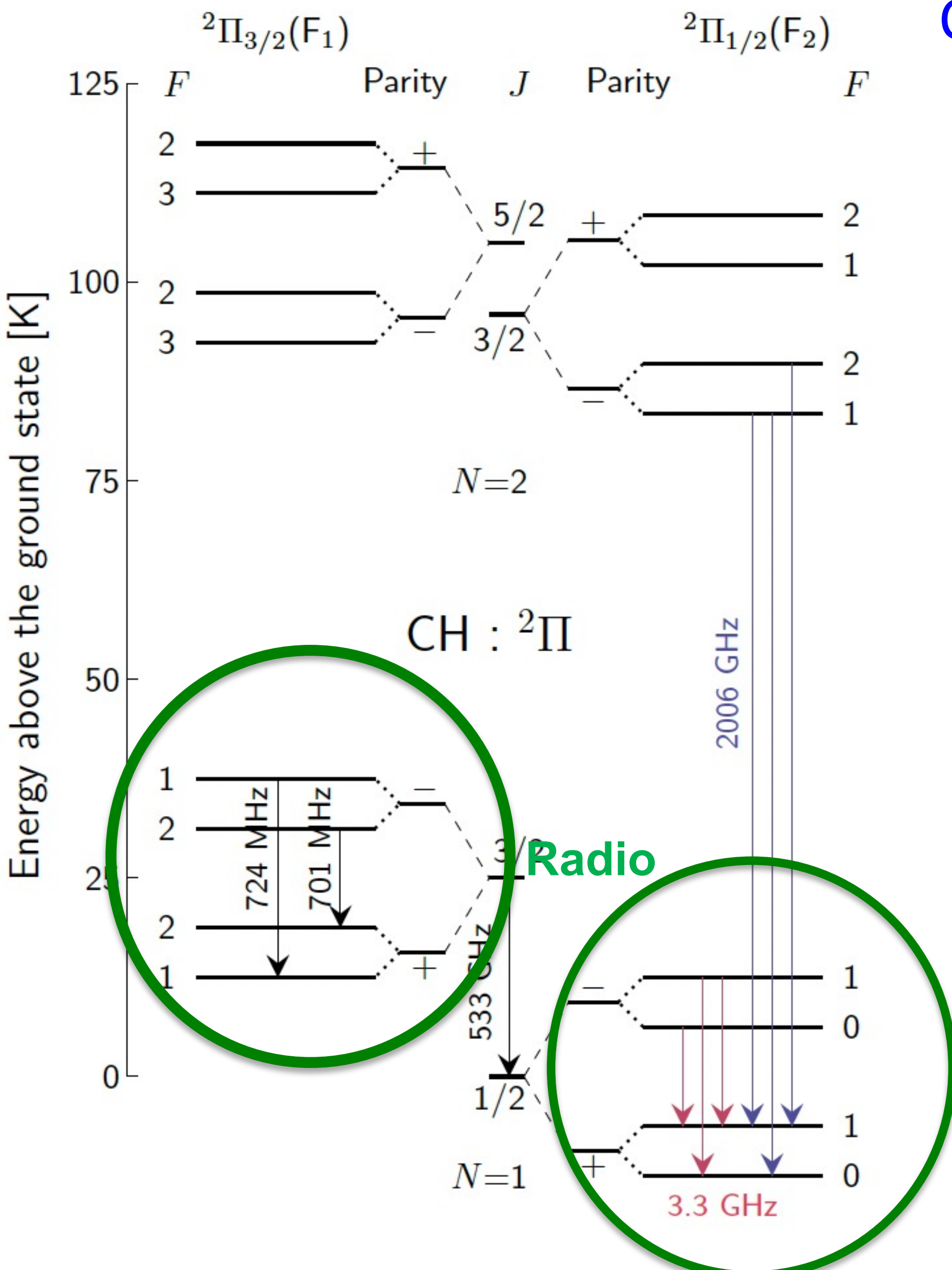


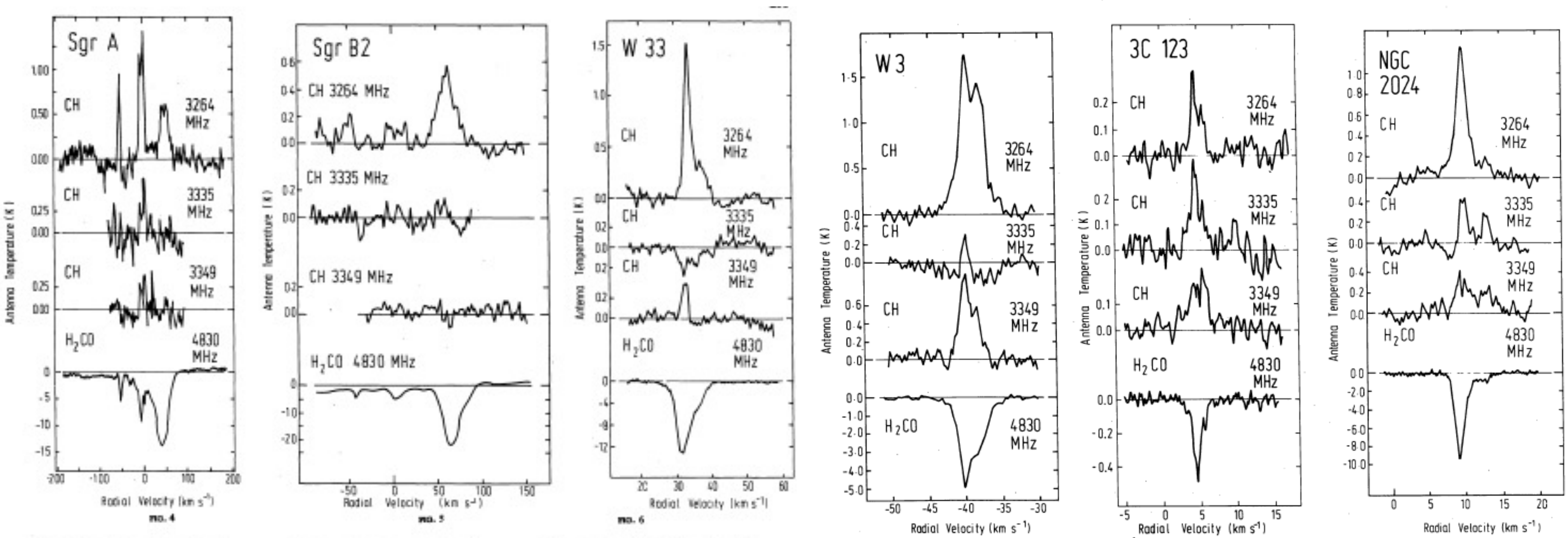
Fig. 8 Emission spectra of the ν_{11} (heavy line), ν_{10} (medium), and ν_{01} (light) lines of the CH ground state Λ doublet, as seen in the direction of W12.

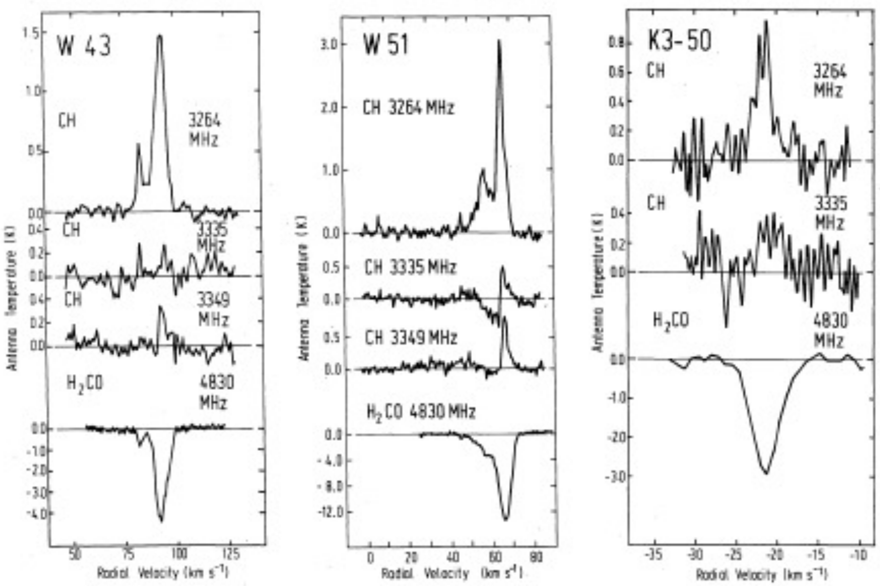
Rydbeck, Elldér & Irvine 1973

CH energy levels



Jacob+ 2021

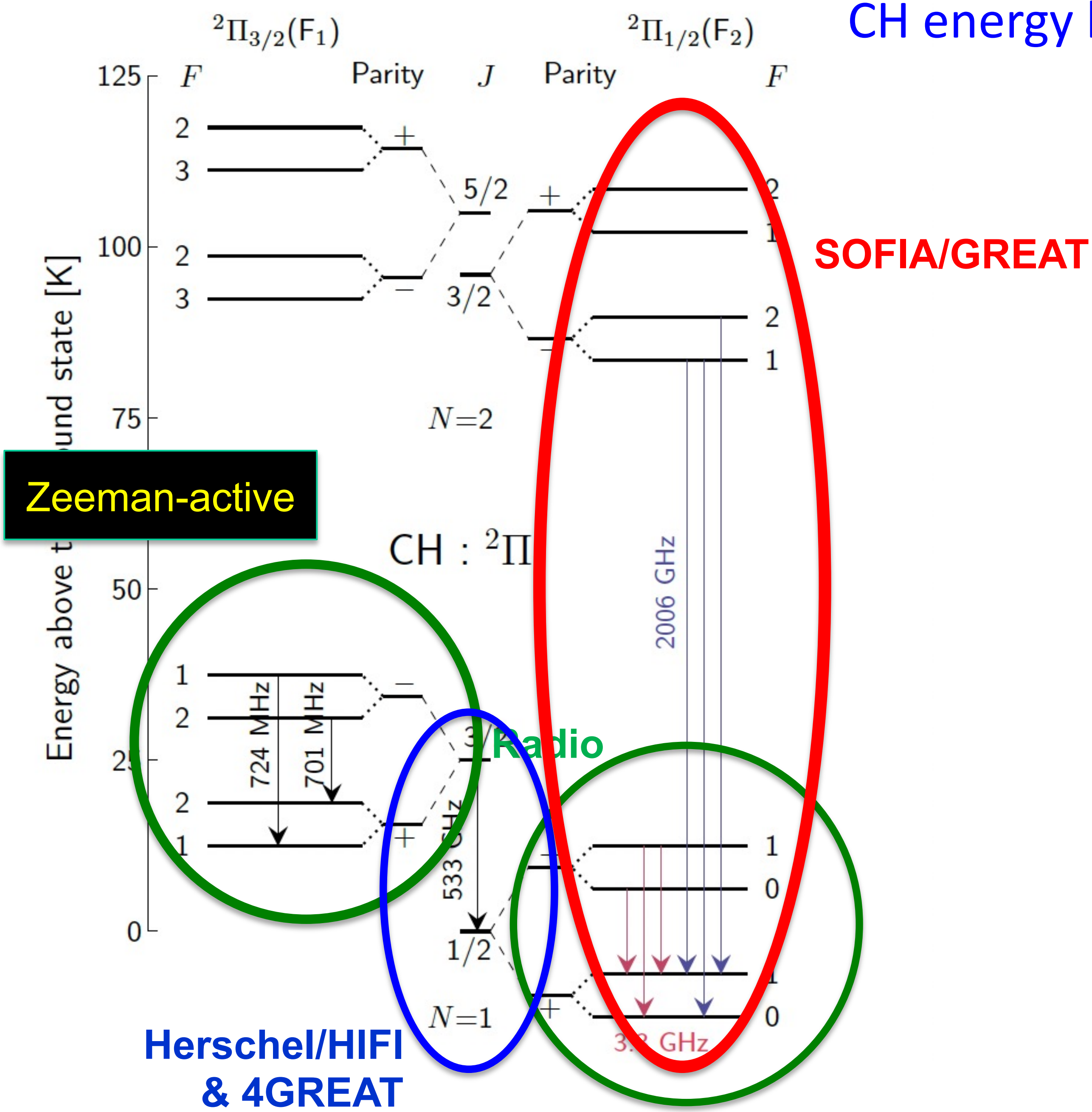




CH ground state hfs lines

Genzel+ 1979

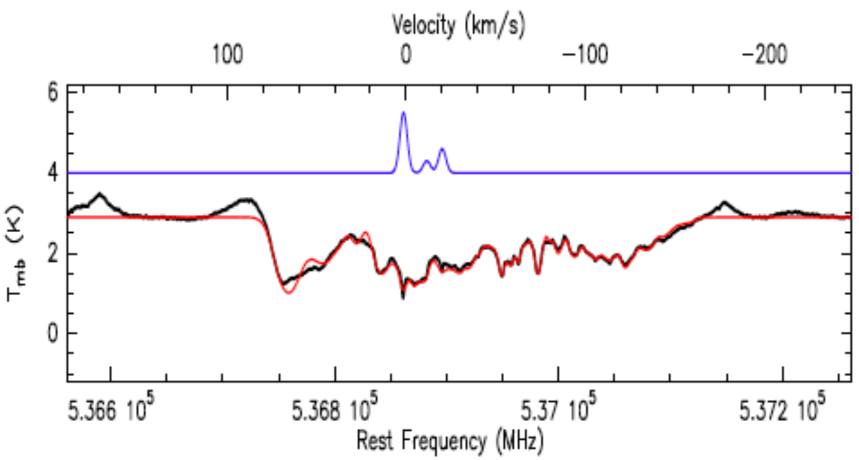
CH energy levels

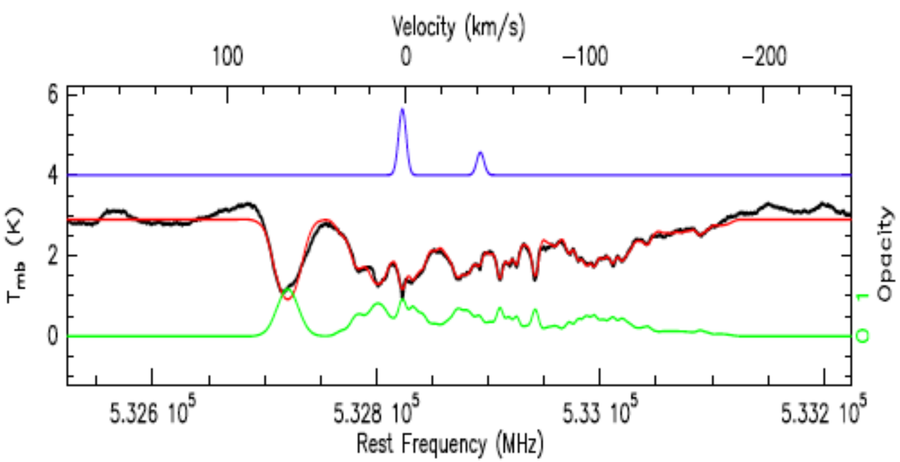


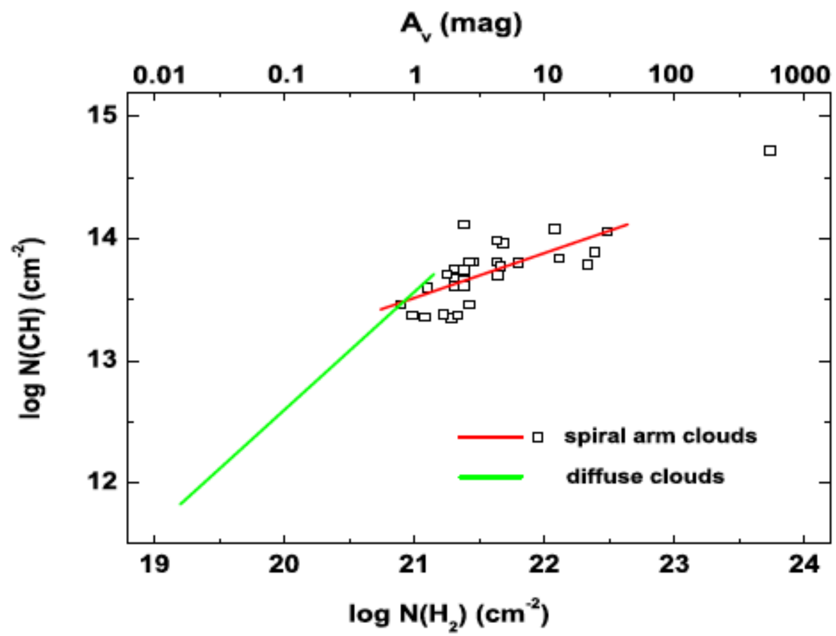
Jacob+ 2021

Herschel observations of EXtra-Ordinary Sources (HEXOS): detecting spiral arm clouds by CH absorption lines★

S.-L. Qin[1], P. Schilke[1,2], C. Comito[2], T. Möller[1], R. Rolffs[2], H. S. P. Müller[1], A. Belloche[2], K. M. Menten[2], D. C. Lis[3],







Sgr B2

A&A 521, L16 (2010)
DOI: 10.1051/0004-6361/201015115

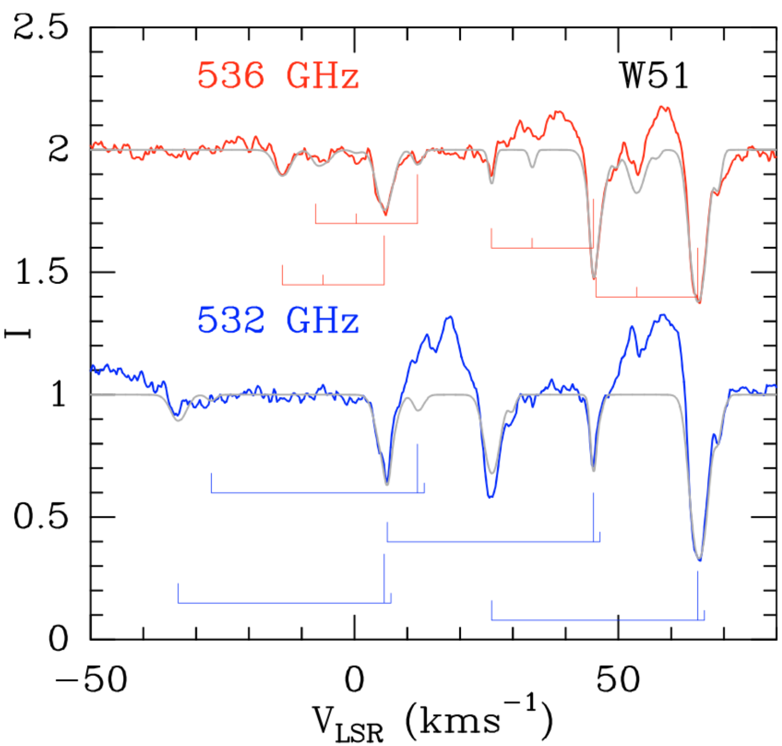
Astronomy & Astrophysics
Special feature

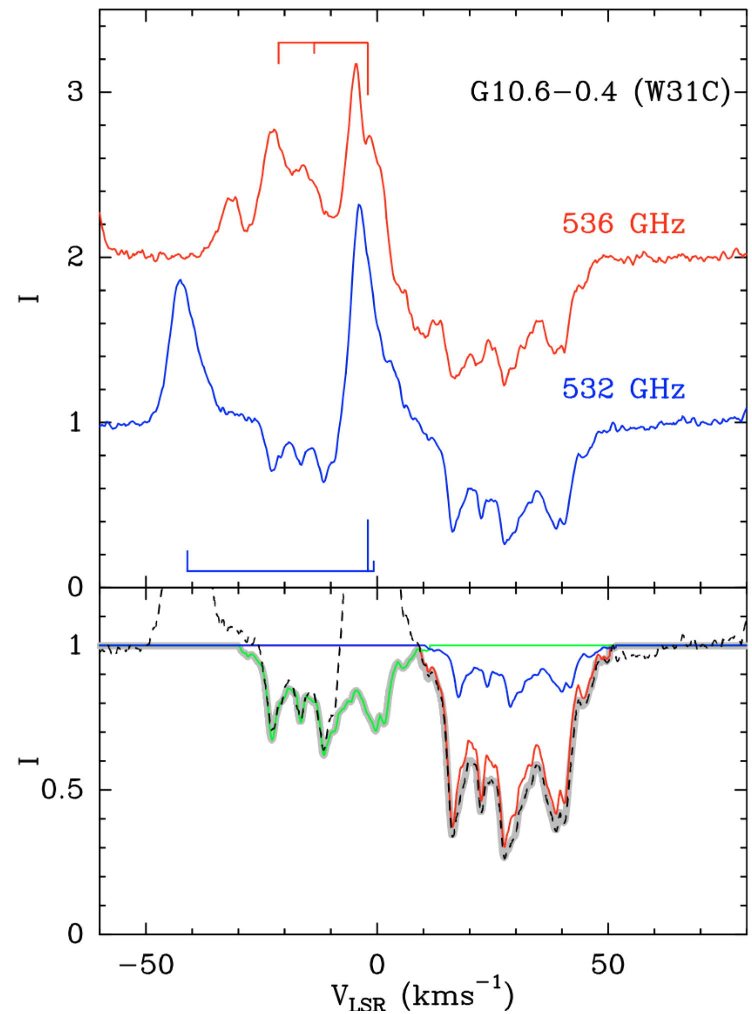
Herschel/HIFI: first science highlights

Letter to the Editor

Interstellar CH absorption in the diffuse interstellar medium along the sight-lines to G10.6–0.4 (W31C), W49N, and W51⋆,⋆⋆

M. Gerin[1], M. De Luca[1], J. R. Goicoechea[2], E. Herbst[3], E. Falgarone[1], B. Godard[1,4], T. A. Bell[5], A. Coutens[6,7], M. Kaźmierczak[8], P. Sonnentrucker[9], J. H. Black[10], D. A. Neufeld[9], T. G. Phillips[5], J. Pearson[11], P. B. Rimmer[3], G. Hassel[3], D. C. Lis[5], C. Vastel[6,7], F. Boulanger[4], J. Cernicharo[2], E. Dartois[4], P. Encrenaz[1], T. Giesen[12], P. F. Goldsmith[11], H. Gupta[11], C. Gry[13], P. Hennebelle[1], P. Hily-Blant[14], C. Joblin[6,7], R. Kołos[15], J. Krełowski[8], J. Martín-Pintado[2], R. Monje[5], B. Mookerjea[16], M. Perault[1], C. Persson[10], R. Plume[17], M. Salez[1], M. Schmidt[18], J. Stutzki[12], D. Teyssier[19], S. Yu[11], A. Contursi[20], K. Menten[21], T. R. Geballe[22], S. Schlemmer[12], P. Morris[23], W. A. Hatch[11], M. Imram[11], J. S. Ward[11], E. Caux[6,7], R. Güsten[21], T. Klein[21], P. Roelfsema[24], P. Dieleman[24], R. Schieder[12], N. Honingh[12], and J. Zmuidzinas[5]





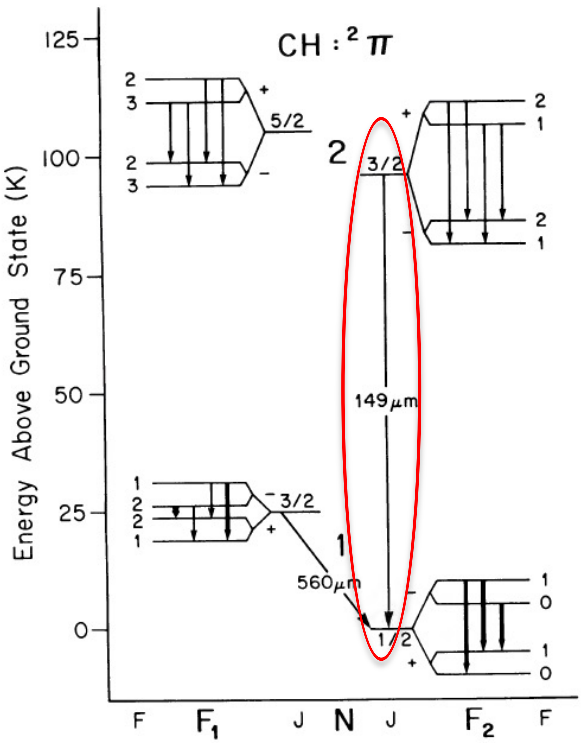
A&A 612, A37 (2018)
https://doi.org/10.1051/0004-6361/201731810

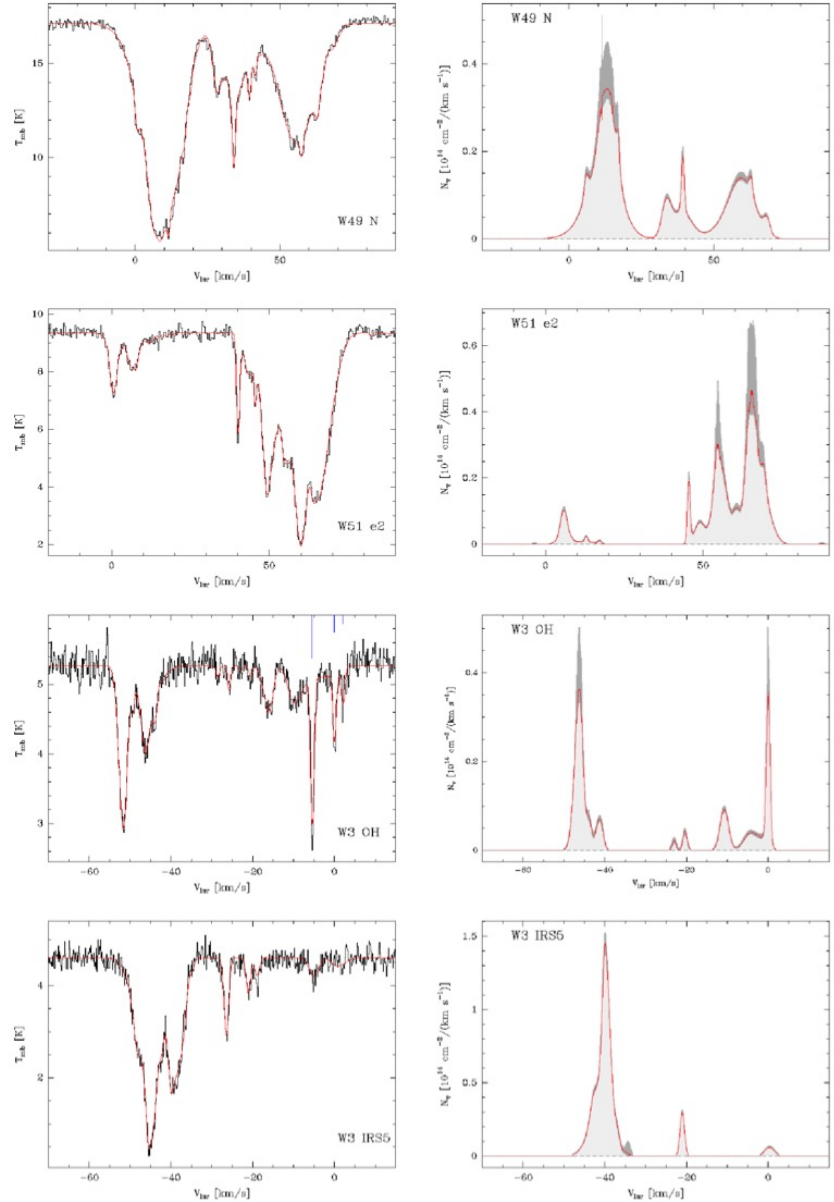
Astronomy & Astrophysics

Unveiling the chemistry of interstellar CH

Spectroscopy of the 2 THz $N = 2 \leftarrow 1$ ground state line★

H. Wiesemeyer[1], R. Güsten[1], K.M. Menten[1], C.A. Durán[1], T. Csengeri[1], A.M. Jacob[1], R. Simon[2], J. Stutzki[2], and F. Wyrowski[1]





- Envelopes of SFRs
- Line of sight diffuse & translucent clouds

A&A 650, A133 (2021)
https://doi.org/10.1051/0004-6361/202140419

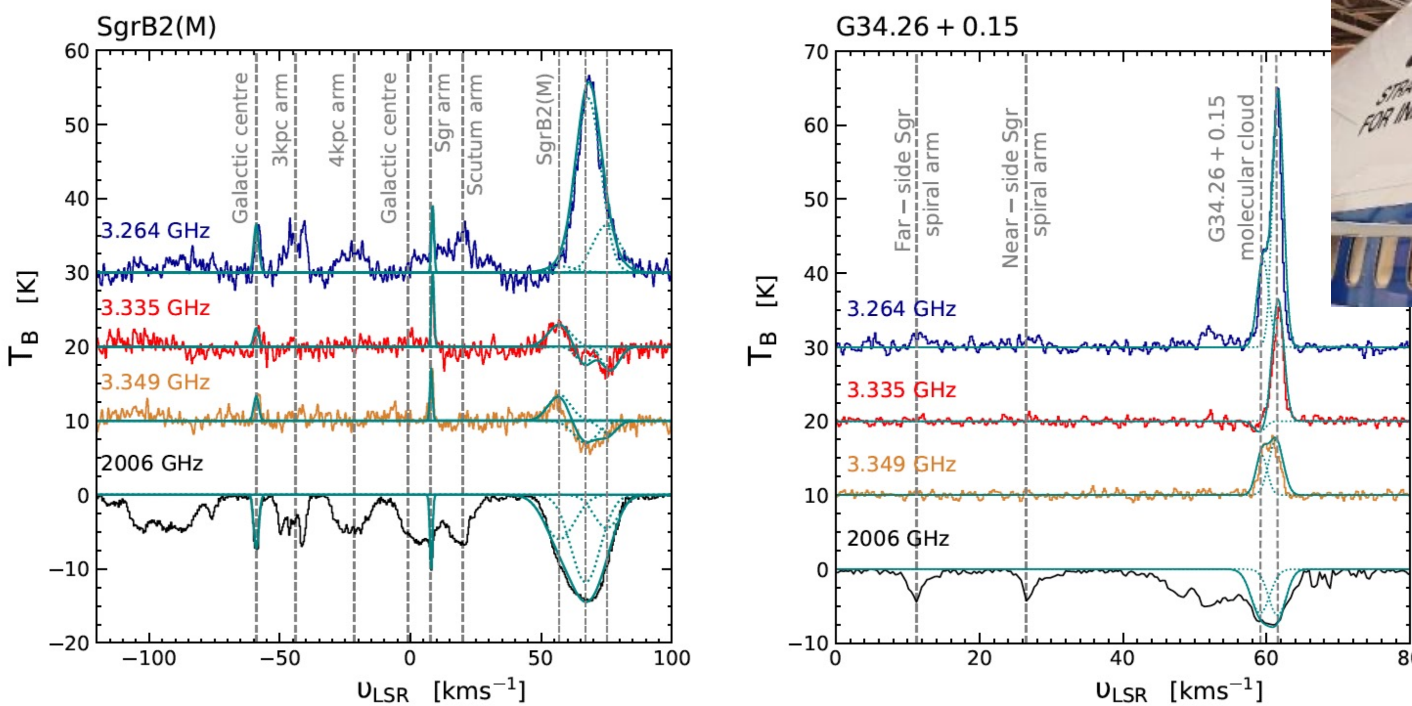
Astronomy & Astrophysics

The CH radical at radio wavelengths: revisiting emission in the 3.3 GHz ground-state lines

Arshia M. Jacob*, Karl M. Menten, Helmut Wiesemeyer, and Gisela N. Ortiz-León

+

Arshia Jacob



- Column densities from FIR rotational line used to “anchor” modeling of radio hfs lines → Inferred temperatures 50–125 K

For OH, see Poster by Michael Busch

THE ASTROPHYSICAL JOURNAL, **292**:L25–L29, 1985 May 1

DETECTION OF INTERSTELLAR ROTATIONALLY EXCITED CH

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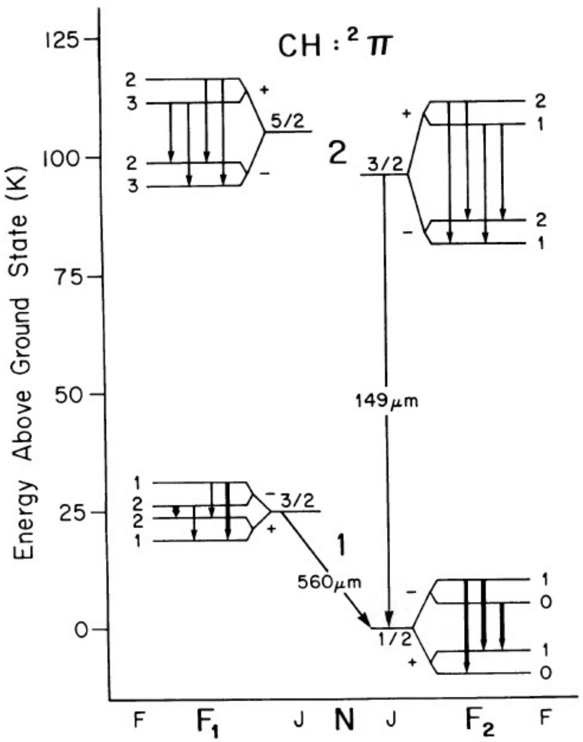
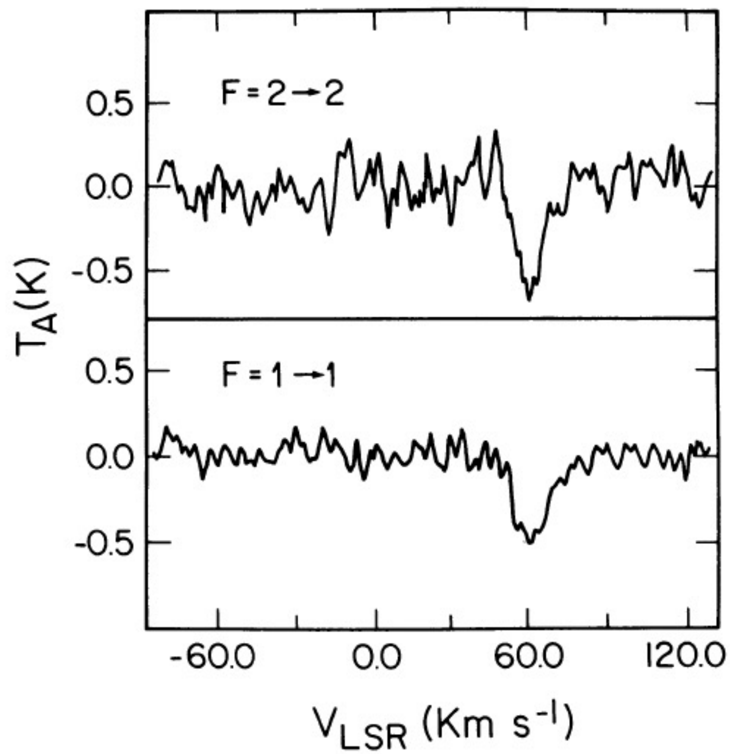
Department of Chemistry and Radio Astronomy Laboratory, University of California, Berkeley
AND
B. E. TURNER
National Radio Astronomy Observatory,[1] Charlottesville, Virginia
Received 1984 September 20; accepted 1985 January 25

Rotationally excited CH





Astron. Astrophys. 161, 329–333 (1986)

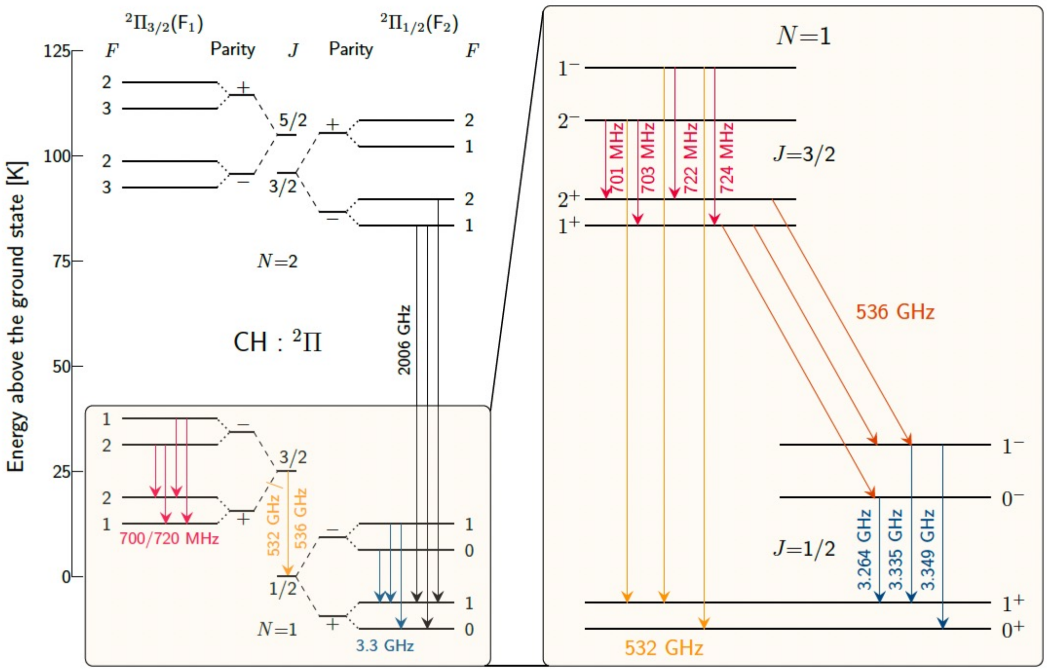
ASTRONOMY AND ASTROPHYSICS

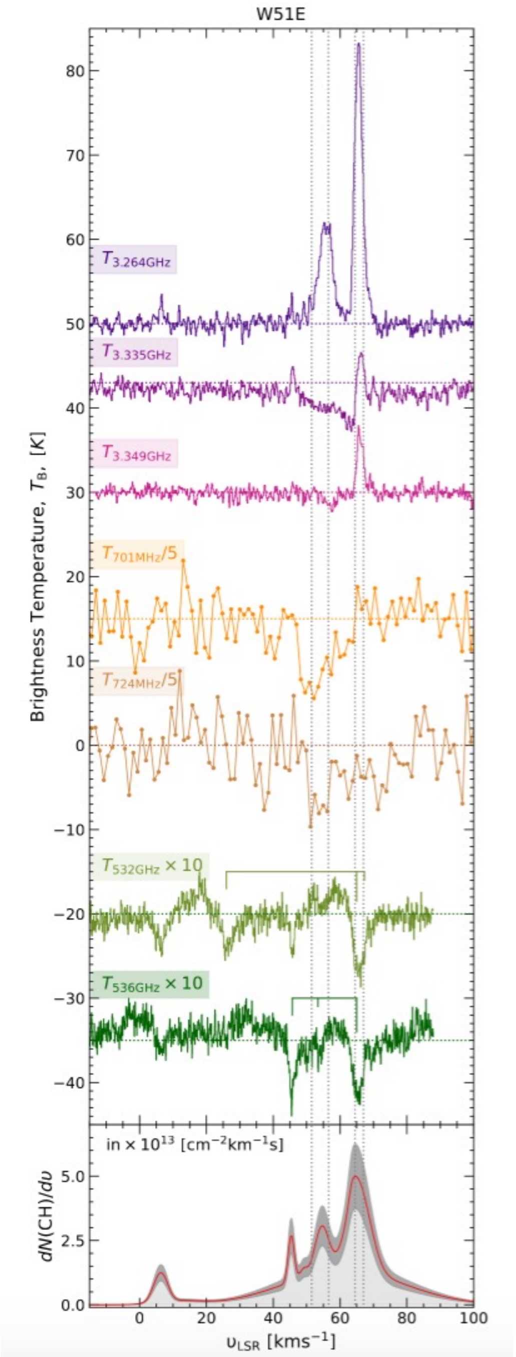
A search for rotationally-excited CH in galactic sources

H.E. Matthews[1], M.B. Bell[1], T.J. Sears[2], B.E. Turner[3], and L.J. Rickard[4]

Zero detections

Transition	J	F	Frequency* (MHz)	Line[a] Strength	A_{ij}** (sec^{-1})	Notes	Energy Above Ground (cm^{-1})
F_1	2½	3^+-2^-	4836.5 ±2.0	0.038	1.52(-11)	a	
		3^+-3^-	4847.84±0.20	0.76	3.07(-10)	b	73
		2^+-2^-	4870.12±0.20	0.53	3.03(-10)	b	
		2^+-3^-	4876.2 ±2.0	0.038	2.19(-11)	a	
F_2	1½	1^+-2^-	7274.4 ±1.0	0.13	4.14(-10)	a	
		1^+-1^-	7325.05±0.15	0.66	2.15(-9)	d	67
		2^+-2^-	7348.18±0.15	1.19	2.34(-9)	d	
		2^+-1^-	7396.7 ±1.0	0.13	2.61(-10)	a	
F_1	3½	4^--3^+	11250.79±0.50	0.016	6.28(-11)	b,c	
		4^--4^+	11265.21±0.15	0.56	2.20(-9)	b	158
		3^--3^+	11287.05±0.15	0.43	2.19(-9)	b	
		3^--4^+	11301.22±0.20	0.016	8.19(-11)	b,c	
F_2	2½	2^--3^+	14713.78±0.15	0.038	6.01(-10)	b	
		2^--2^+	14756.81±0.15	0.53	8.45(-9)	b	153
		3^--3^+	14778.97±0.20	0.76	8.70(-9)	b	
		3^--2^+	14821.88±0.15	0.038	4.39(-10)	b	
F_1	4½	5^+-4^-	19933.3 ±3.0	0.008	1.43(-10)	a	
		5^+-5^-	19949.9 ±3.0	0.44	7.88(-9)	a	270
		4^+-4^-	19971.8 ±3.0	0.36	7.91(-9)	a	
		4^+-5^-	19988.4 ±3.0	0.008	1.76(-10)	a	
F_2	3½	3^+-4^-	24381.57±0.4	0.016	8.22(-10)	b	
		3^+-3^-	24420.65±0.1	0.43	2.22(-8)	b	267
		4^+-4^-	24442.56±0.1	0.55	2.21(-8)	b	
		4^+-3^-	24482.10±0.2	0.016	6.47(-10)	b,c	





VLA

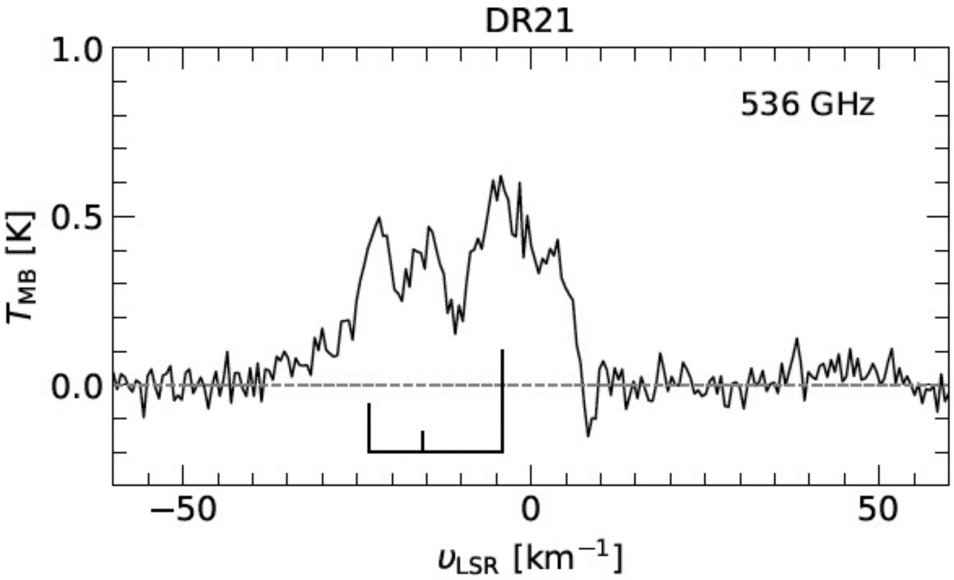
uGMRT

Herschel/ HIFI

- Rot. excited 700 MHz hfs lines are extremely weak
- Litte chance of Zeeman effect detection (SKA?)

Jacob+ 2024

4GREAT



Jacob+ 2024

Monthly Notices
of the
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MNRAS **475,** 5480–5486 (2018) doi:10.1093/mnras/sty193
Advance Access publication 2018 January 24

Hyperfine excitation of CH in collisions with atomic and molecular hydrogen

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OH – H
and OH-H_2

OH and CH with SOFIA

- SOFIA/GREAT observations gave access to fundamental rotational lines of CH and OH (and OD)
- Submillimeter/FIR lines provide foundation for modeling of radio-wavlength hfs lines
  - assisted by new collisional rate coefficients
- Both CH and OH probe the larger scale environment of high mass YSOs
- Rotationally excited OH probes their immediate neighborhoods
  - modeling of chemistry desirable
- Very little rotationally excited CH

GREAT - the Consortium

SOFIA PI-Instrument funded and developed by

- MPI Radioastronomie (2.7 THz channel)
  - R. Güsten (Co-PI)
  - S. Heyminck (system engineer)
  - B. Klein (FFT spectrometer)
  - I. Camara, T. Klein (2.7 THz LO)
- Univ. zu Köln, KOSMA (1.4/1.9THz channels)
  - J. Stutzki (Co-PI)
  - U. Graf (1.4 &1.9THz LO, Optics)
  - K. Jacobs (HEB mixers up to 2.7 THz)
  - R. Schieder (array-AOS)
- DLR Planetenforschung (4.7 THz channel)
  - H-W. Hübers (Co-PI: 4.7 THz HEB, IF, cal unit)
- MPI Sonnensystemforschung
  - P. Hartogh et al. (CO-PI: CTS)

Astronomical thanks to: Arshia Jacob, Helmut Wiesemeyer, Friedrich Wyrowski, Timea Csengeri + …