Zeeman Splitting Opportunities with the ngVLA

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THE
ASTROPHYSICAL JOURNAL
AN INTERNATIONAL REVIEW OF SPECTROSCOPY
AND ASTRONOMICAL PHYSICS

Zeeman 1897
ApJ, Vol 5

ON THE INFLUENCE OF MAGNETISM ON THE NATURE OF THE LIGHT EMITTED BY A SUBSTANCE.[1]

By P. ZEEMAN.

1. SEVERAL years ago, in the course of my measurements concerning the Kerr phenomenon, it occurred to me whether the light of a flame if submitted to the action of magnetism would perhaps undergo any change. The train of reasoning by which I attempted to illustrate to myself the possibility of this is of minor importance at present;[2] at any rate I was induced thereby to try the experiment. With an extemporized apparatus the spectrum of a flame, colored with sodium, placed between the poles of a Ruhmkorff electro-magnet, was looked at. The result was negative. Probably I should not have tried this experiment again so soon had not my attention been drawn some two years ago to the following quotation from Maxwell's sketch of Faraday's life. Here (Maxwell, *Collected Works*, II, 790) we read: "Before we describe this result we may mention that in 1862 he made the relation between magnetism and light the subject of his very last experimental work. He endeavored, but in vain, to detect any change in the lines of the spectrum of a flame when the flame was acted on by a powerful magnet." If a Faraday[3] thought of the possibility of the above-mentioned relation, perhaps it might be yet worth while to try the experiment again with the excellent auxiliaries of spectroscopy of the present time, as I am not aware that it has been done by others.[4] I will take the liberty of stating briefly to the readers of the *Philosophical Magazine* the results I have obtained up till now.

Bolton & Wild 1957
ApJ, 125, 256

ON THE POSSIBILITY OF MEASURING INTERSTELLAR MAGNETIC FIELDS BY 21-CM ZEEMAN SPLITTING

Measurement of the small magnetic field believed to exist in interstellar space has so far eluded both optical and radio techniques. However, the introduction of large radio reflectors offers the possibility of determining longitudinal fields in localized interstellar regions by observing the Zeeman splitting of the 21-cm line of neutral hydrogen.

In the presence of a weak magnetic field, the 21-cm line is split into three components, of frequency (Nafe and Nelson 1948)

$$\nu_0 \qquad (\pi)\,, \quad \textbf{1420.4058 MHz}$$

$$\nu_0 \pm \frac{eH}{4\pi m c} \qquad (\sigma)\,, \quad \textbf{1.4 Hz/}\boldsymbol{\mu}\textbf{G}$$

where ν_0 is the undisplaced frequency of the line and H the longitudinal component of the magnetic field. Numerically, the frequency difference, $\Delta\nu$, between the two σ components is 2.8 Mc/s per gauss. Thus a magnetic field of 10^{-5} gauss, such as is believed to exist in the Galaxy, gives $\Delta\nu \approx 30$ c/s.

Under normal circumstances the detection of such small shifts in the galactic emission profiles would hardly be possible, owing to their large Doppler broadening. On the other hand, relatively narrow profiles have been observed in absorption. Hagen, Lilley, and McClain (1955) have reported three narrow absorption lines in the 21-cm spectrum of the discrete source in Cassiopeia, presumably due to three individual H I concentrations with different radial velocities. These lines have half-widths of about 10 kc/s, in the center of which the radiation is almost completely absorbed. It may reasonably be assumed that the magnetic field is sensibly constant in direction over any one of the H I concentrations responsible for the absorption lines.

The detection of a Zeeman shift less than 1 per cent of the line width could be accomplished by using the radio analogue of the optical method currently employed by Babcock (1953) for measuring weak solar fields. The frequency of a narrow-band receiver is set on the edge of the line near the point of maximum steepness, and the polarization of the antenna is switched to receive the two circular components alternately. The output at the switching frequency is given, in units of antenna temperature, by

$$\Delta T = \frac{T_a \Delta\nu}{\mu}\,,$$

where T_a is the maximum decrease in antenna temperature of the absorption line, $\Delta\nu = 2.8 \times 10^6 H$ c/s is the difference in frequencies between the two σ components, and μ is the half-width of the absorption line, assumed of gaussian profile. Current results indicate values of T_a of the order of 1000° K if the Cassiopeia absorption lines are observed with a 150-foot reflector. Hence, with $\mu = 10$ kc/s, we should expect $\Delta T \approx 3 \times 10^5 H$ degrees. Current techniques permit the detection of $\Delta T \approx 1°$ K ($H \approx 3 \times 10^{-6}$ gauss), and instrumental improvements on this figure are likely in the future.

POSITIVE DETERMINATION OF AN INTERSTELLAR MAGNETIC FIELD BY MEASUREMENT OF THE ZEEMAN SPLITTING OF THE 21-cm HYDROGEN LINE

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National Radio Astronomy Observatory,* Green Bank, West Virginia
(Received 17 July 1968)

Fields of the order of 2×10^{-5} G exist in the Perseus spiral arm in the direction of the radio source Cassiopeia A.

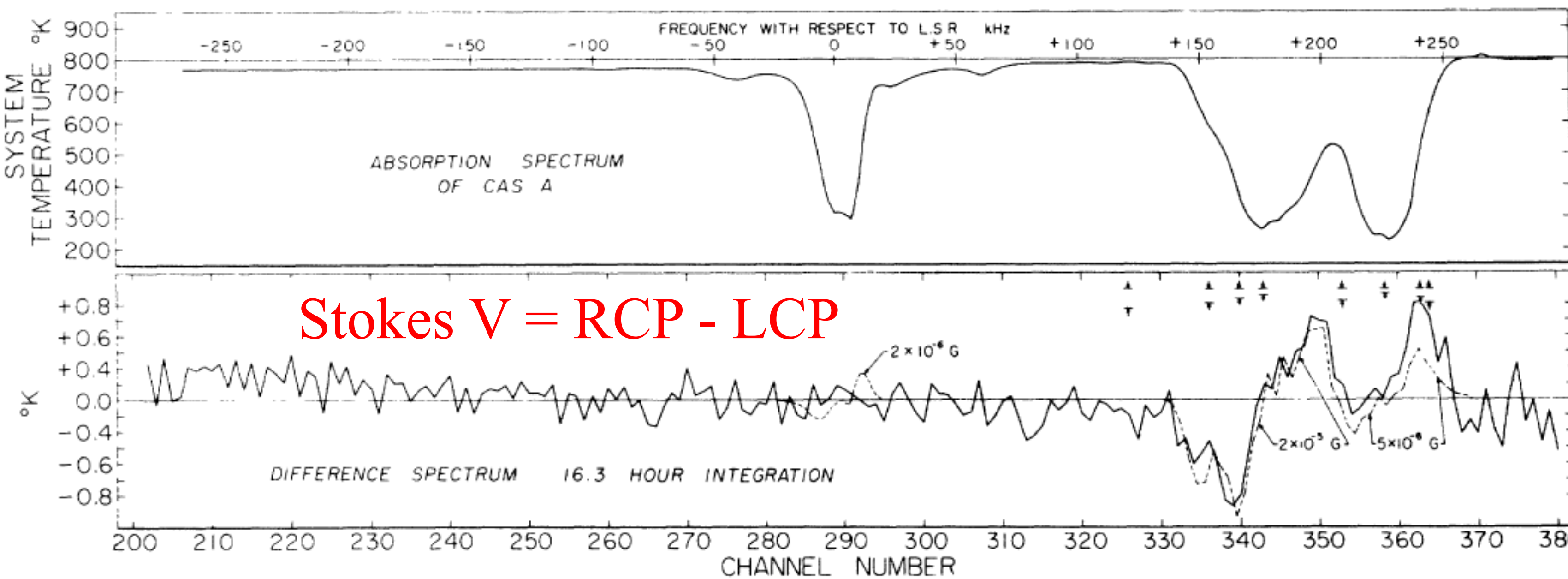


FIG. 1. The absorption spectrum of Cas A, together with the difference spectrum, right-hand minus left-hand polarization, incident on the feed representing 16.3 h of integration. Frequencies with respect to the local standard of rest are indicated. Arrowed bars represent expected peak-to-peak noise at various parts of the spectrum.

The Zeeman Effect

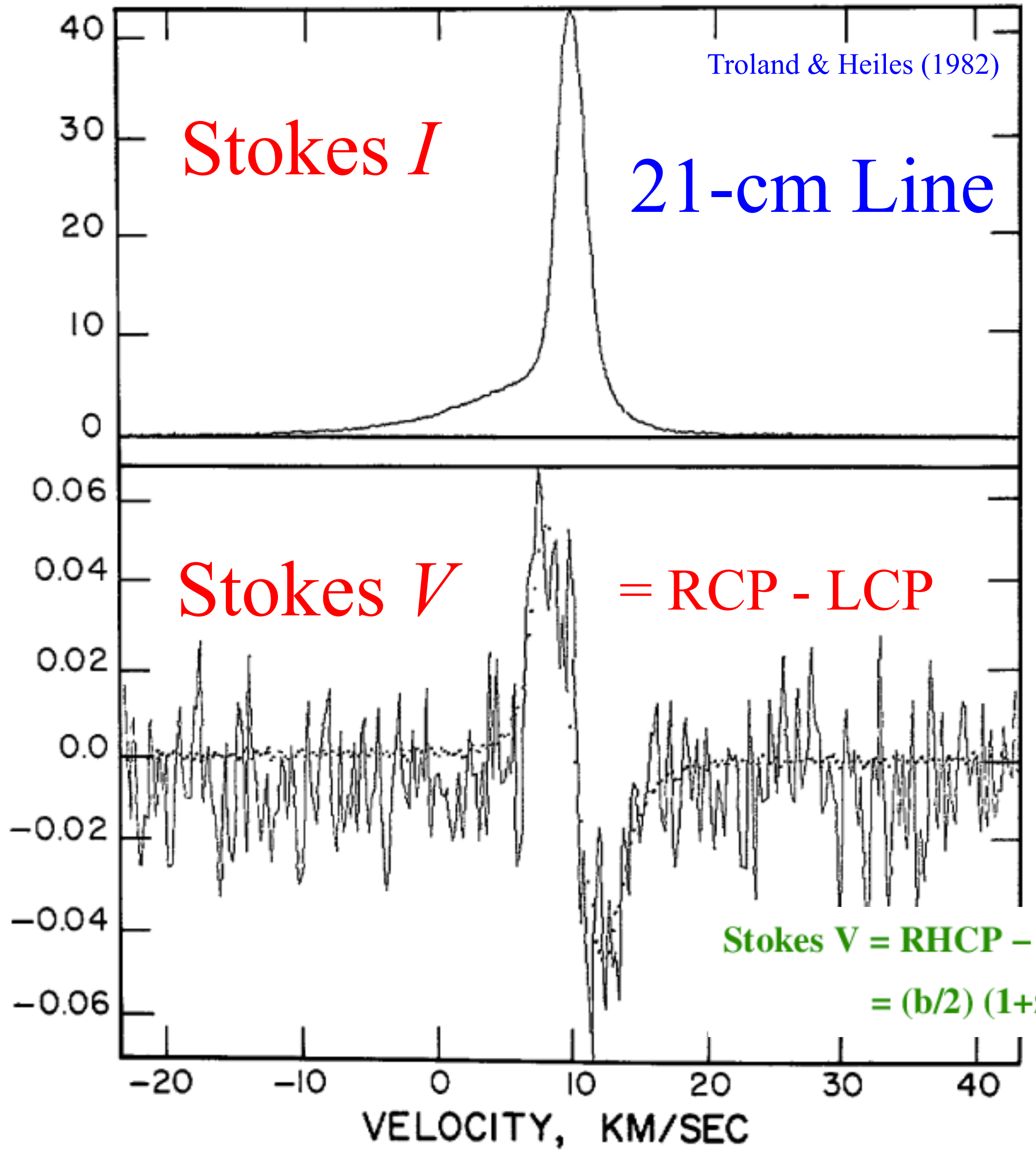
- Reveals *in situ* **B** fields in neutral ISM.

- Splitting is much smaller than line width.
  - Can probe only line-of-sight component of *B*.
  - Get both field strength and direction.

- Complementary to Faraday rotation.
  - RMs probe *B* in ionized magnetized plasma.

- **Completely limited by sensitivity.**

The Zeeman Effect

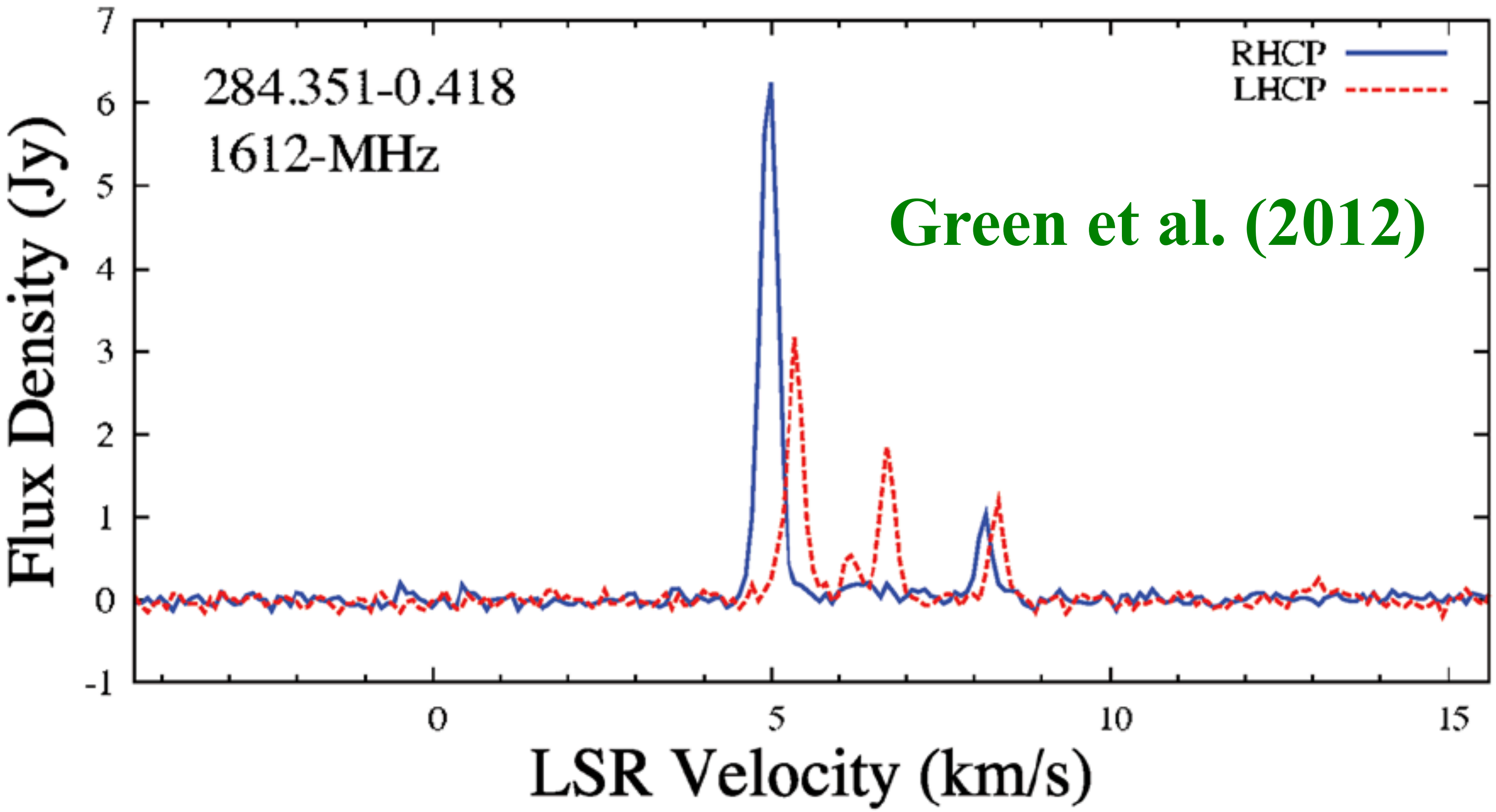


Stokes V = RHCP – LHCP

$= (b/2)\ (1+z)^{-1}\ dI/d\nu\ B_{los} + \alpha I$

The Zeeman Effect

OH masers are so narrow, they can be <u>fully split</u> and yield <u>total</u> *B* field.



ngVLA Science Use Case **# XX**

Polarization science with the ngVLA

C. Hull, J.M. Girart, T. Robishaw, T. Bourke

I. Science Goal(s)

Briefly (in a sentence or two) summarize the key science goal(s) for this science case.

The goal of this science case is to use the polarization capabilities of the ngVLA to explore a wide range of phenomena including (1) magnetic fields in protostellar cores and protoplanetary disks via polarized emission from magnetically aligned dust grains and spectral lines, including in regions optically thick at ALMA wavelengths, (2) polarization from dust scattering in disks, (3) spectral-line polarization from the Zeeman and Goldreich-Kylafis effects, and (4) magnetic fields in protostellar jets and OB-star-forming cores via synchrotron emission.

Cosmic Magnetism is not a key science working group for ngVLA, but…

Splitting Coefficients for Zeeman Transitions

Species	Transition	ν (GHz)	b (Hz μG^{-1})	Ref.
Atomic Transitions				
H I.........	$^2S_{1/2}, F = 1\text{–}0$	1.420406	2.80	1
H I.........	H$n\alpha$ recombination lines	...	2.80	1
C II	C$n\alpha$ & C$n\beta$ recombination lines	...	2.80	2
Molecular Transitions				
[redacted]				
OH	$^2\Pi_{3/2}, J = 3/2, F = 1\text{–}2$	1.6122	1.308	1
OH	$^2\Pi_{3/2}, J = 3/2, F = 1\text{–}1$	1.6654	3.270	1
OH	$^2\Pi_{3/2}, J = 3/2, F = 2\text{–}2$	1.6673	1.964	1
OH	$^2\Pi_{3/2}, J = 5/2, F = 2\text{–}1$	1.7205	1.308	1
OH	$^2\Pi_{3/2}, J = 5/2, F = 2\text{–}3$	6.0167	0.678	1
OH	$^2\Pi_{3/2}, J = 5/2, F = 2\text{–}2$	6.0307	1.582	1
OH	$^2\Pi_{3/2}, J = 5/2, F = 3\text{–}3$	6.0350	1.132	1
OH	$^2\Pi_{3/2}, J = 5/2, F = 3\text{–}2$	6.0490	0.678	1
CH_3OH	$J_N = 5_1\text{–}6_0 A^+$	6.668512	0.0011	8
C_4H........	$N = 1\text{–}0, J = 3/2\text{–}1/2, F = 0\text{–}1$	9.493061	−2.457	3
C_4H........	$N = 1\text{–}0, J = 3/2\text{–}1/2, F = 1\text{–}2$	9.497616	0.897	3
CCS	$J_N = 1_0\text{–}0_1$	11.119446	0.813	5
SO.........	$J_N = 1_2\text{–}1_1$	13.044000	1.93	6
OH	$^2\Pi_{3/2}, J = 7/2, F = 3^+\text{–}3^-$	13.434637	1.06	4
OH	$^2\Pi_{3/2}, J = 7/2, F = 4^+\text{–}4^-$	13.441417	0.795	4
C_4H........	$N = 2\text{–}1, J = 5/2\text{–}3/2, F = 1\text{–}2$	19.014720	1.30	1
C_4H........	$N = 2\text{–}1, J = 5/2\text{–}3/2, F = 2\text{–}3$	19.015144	0.93	1
CCS	$J_N = 2_1\text{–}1_0$	22.344033	0.767	5
SO.........	$J_N = 1_0\text{–}0_1$	30.001630	1.740	5
CCS	$J_N = 3_2\text{–}2_1$	33.751374	0.702	5
CCS	$J_N = 4_3\text{–}3_2$	45.379033	0.629	5
[redacted]				
SO.........	$J_N = 2_2\text{–}1_1$	86.094	0.47	1
C_2H........	$N = 1\text{–}0, J = 3/2\text{–}1/2, F = 2\text{–}1$	87.316925	1.40	1
SO.........	$J_N = 3_2\text{–}2_1$	99.299875	1.043	5
CN.........	$N = 1\text{–}0, J = 1/2, F = 1/2\text{–}3/2$	113.14434	2.18	7
CN.........	$N = 1\text{–}0, J = 1/2, F = 3/2\text{–}1/2$	113.17087	−0.31	7
CN.........	$N = 1\text{–}0, J = 1/2, F = 3/2\text{–}3/2$	113.19133	0.62	7
CN.........	$N = 1\text{–}0, J = 3/2\text{–}1/2, F = 3/2\text{–}1/2$	113.48839	2.18	7
CN.........	$N = 1\text{–}0, J = 3/2\text{–}1/2, F = 5/2\text{–}3/2$	113.49115	0.56	7
CN.........	$N = 1\text{–}0, J = 3/2\text{–}1/2, F = 1/2\text{–}1/2$	113.49972	0.62	7
CN.........	$N = 1\text{–}0, J = 3/2\text{–}1/2, F = 3/2\text{–}3/2$	113.59972	1.62	7
[redacted]				

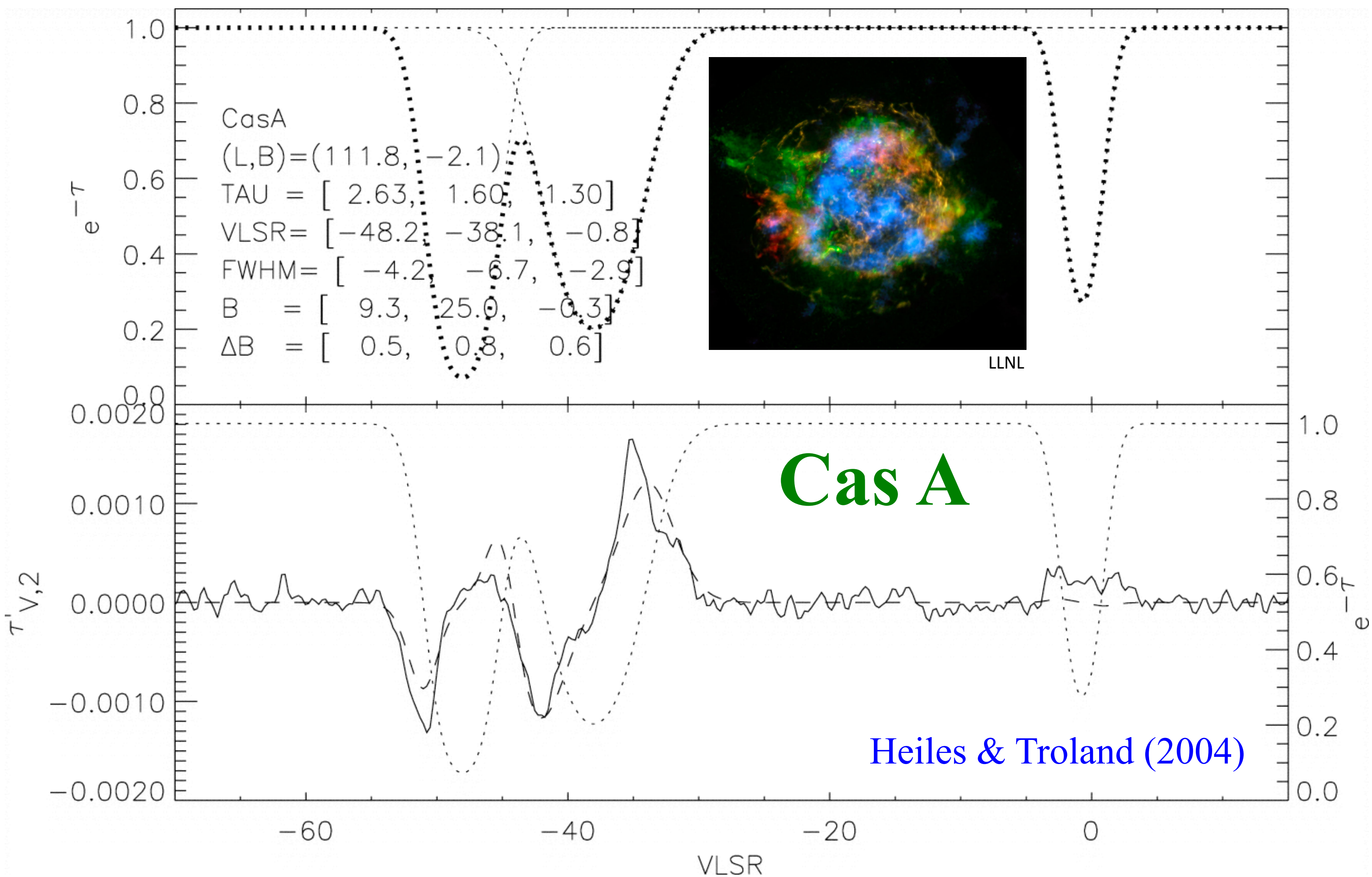
Splitting coefficients measured in lab or calculated quantum mechanically.

Free radicals with an unpaired electron in outer shell give largest Zeeman splitting.

Where's ALMA?
Cycle 5, no full-Stokes. Learn from this when planning ngVLA.

- 4 GHz OH
- 22 GHz H_2O
- 12.2, 36 & 44 GHz Methanol Masers

HI & OH Absorption against Continuum Sources



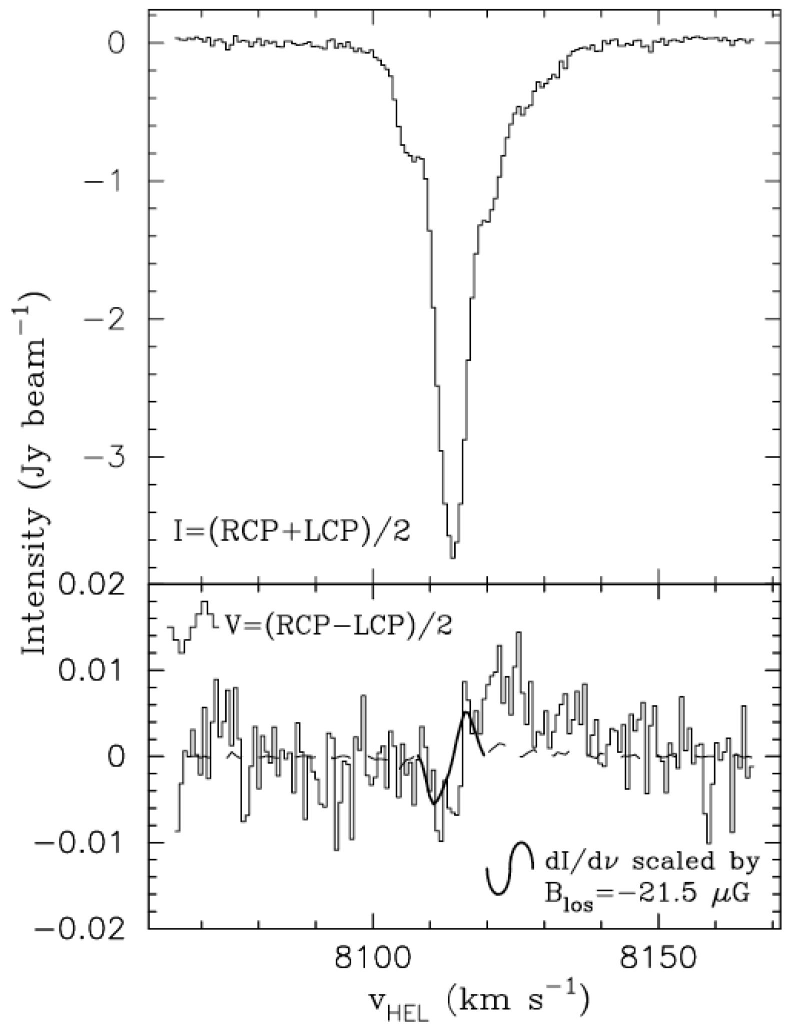
The Astronomical Journal, 130:2566–2570, 2005 December

VERY LARGE ARRAY H i ZEEMAN OBSERVATIONS OF NGC 1275 (PERSEUS A)

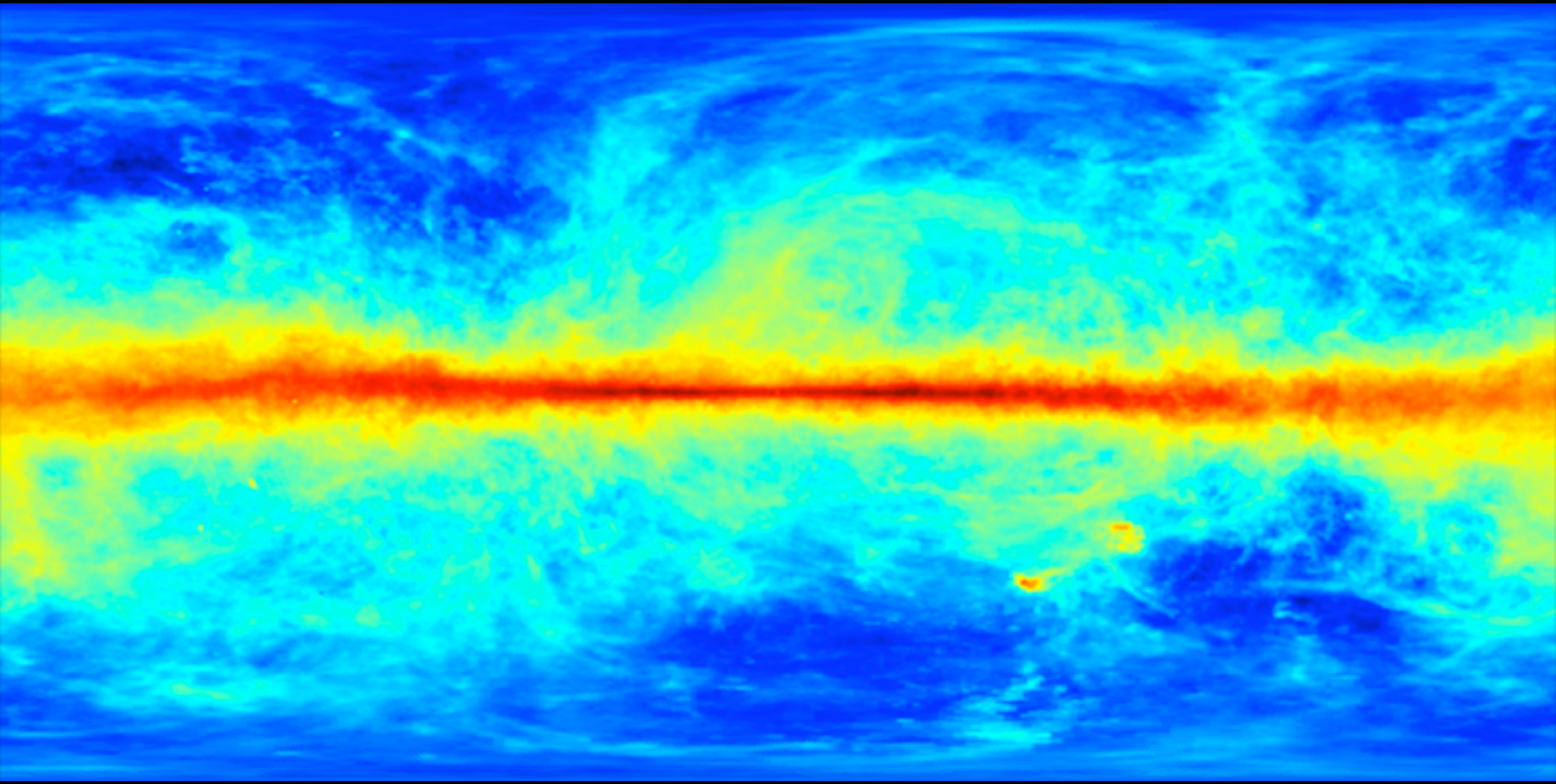
A. P. Sarma,[1] E. Momjian,[2] T. H. Troland,[3] and R. M. Crutcher[4]

Received 2005 April 5; accepted 2005 August 30

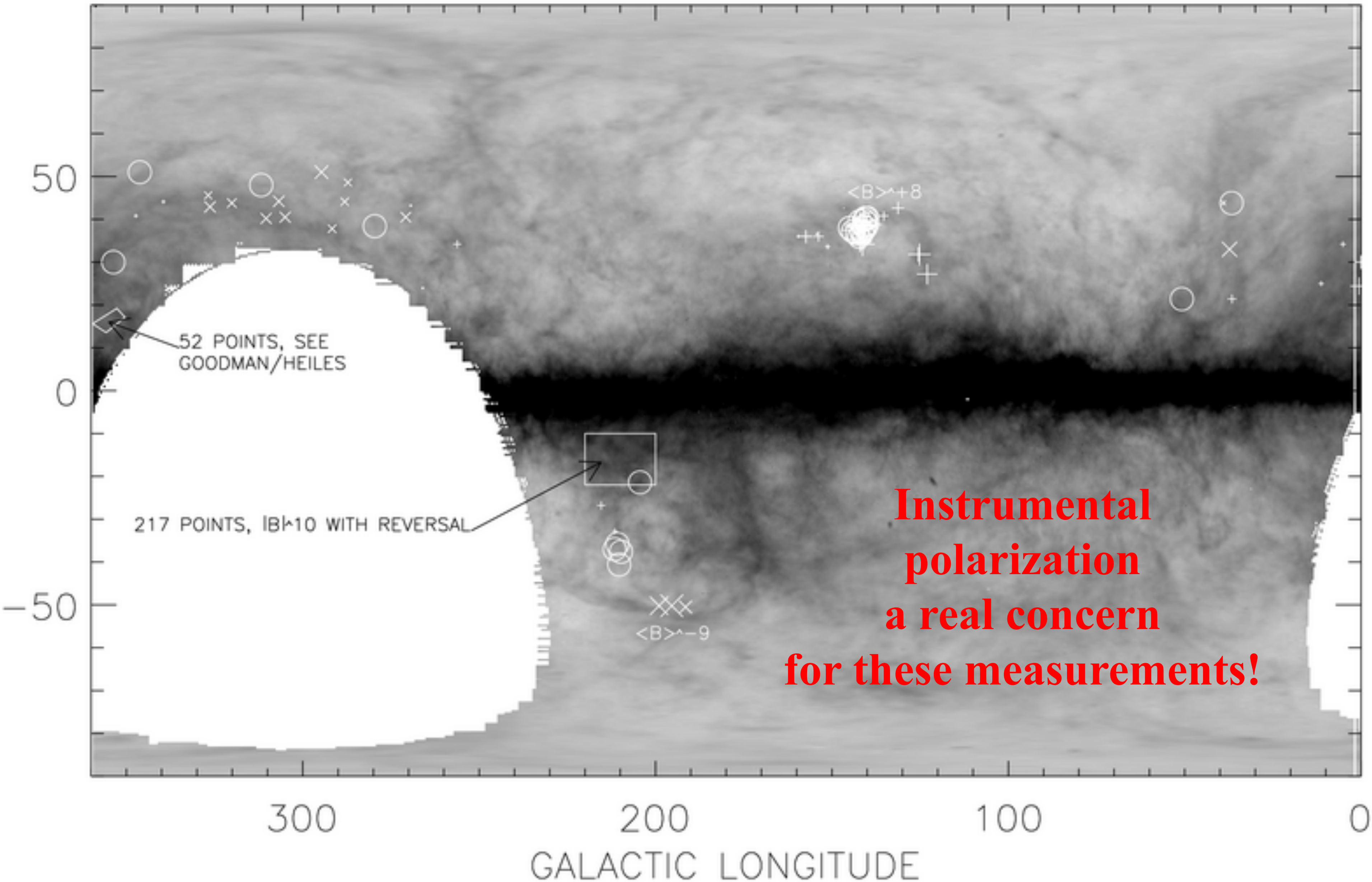
NGC 1275



Diffuse 21-cm Emission



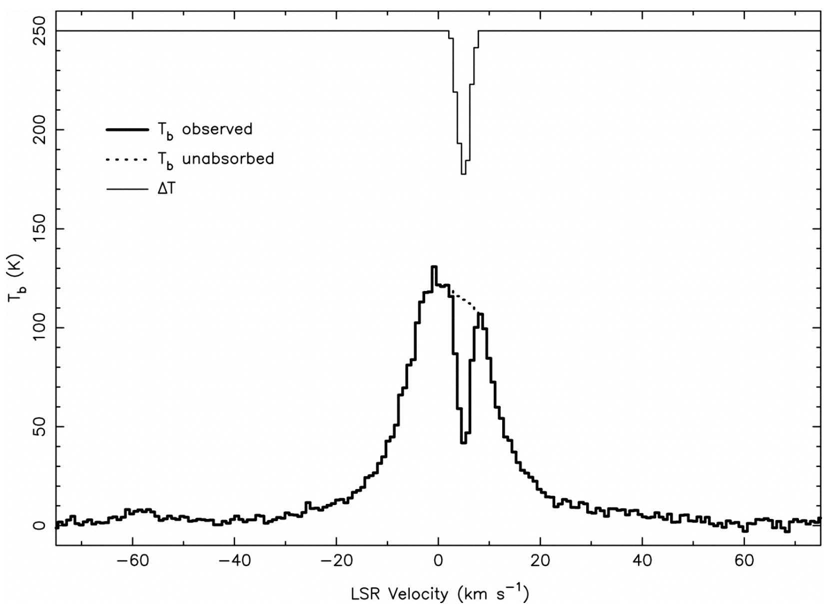
Diffuse 21-cm Emission



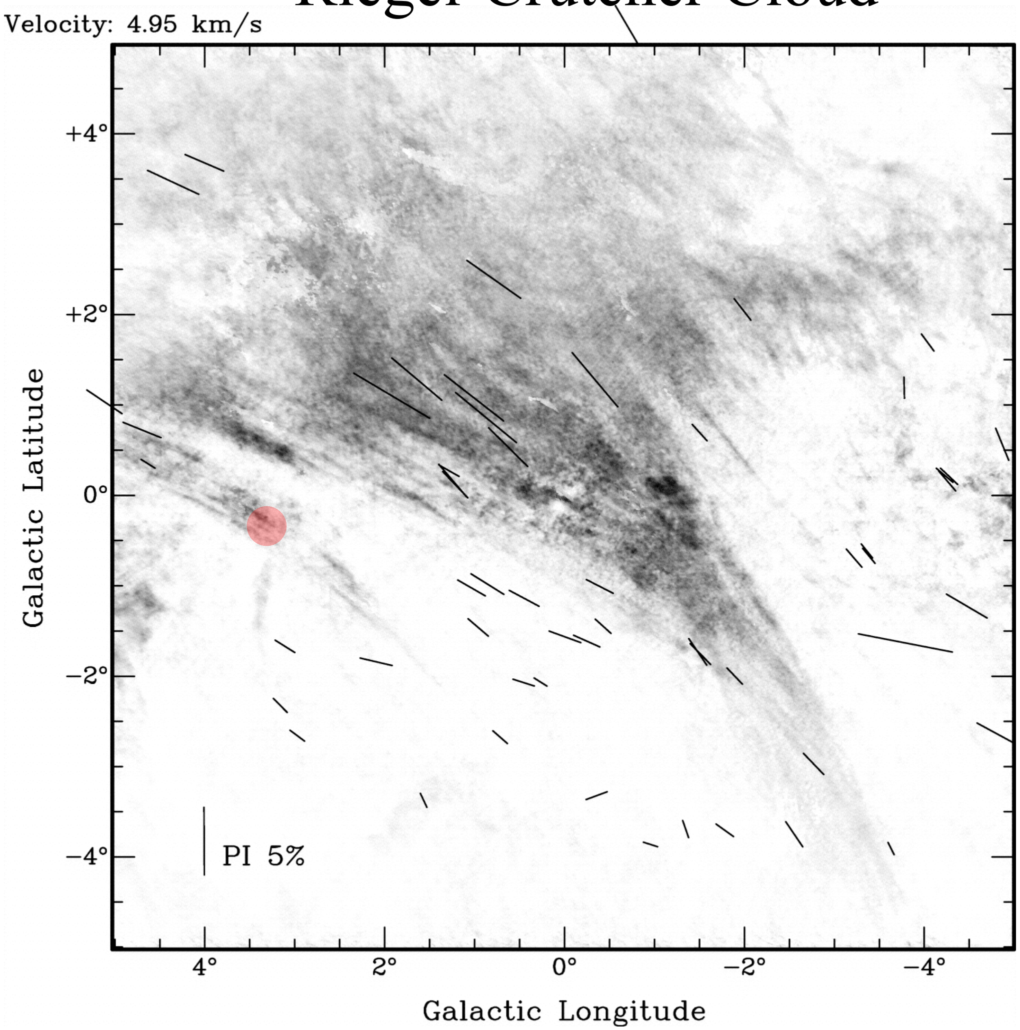
Instrumental polarization a real concern for these measurements!

21-cm HI Self-Absorption

McClure-Griffiths et al. (2006)

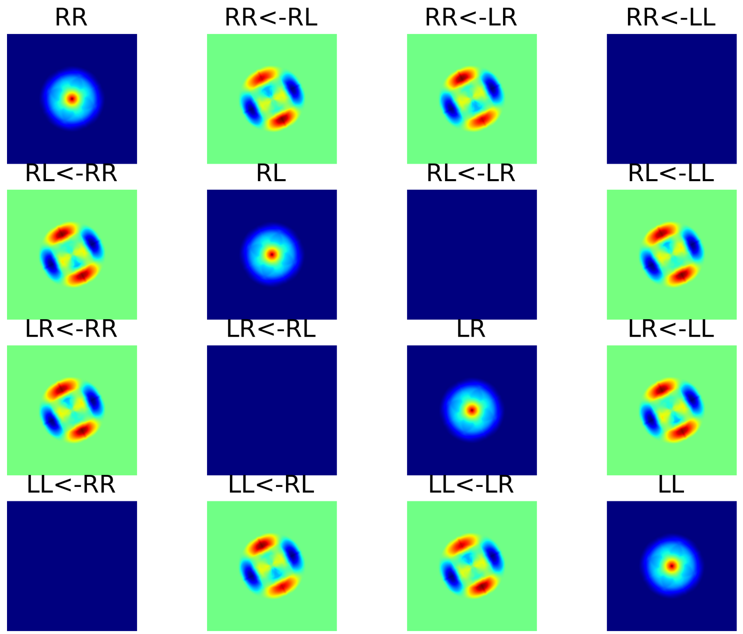


Riegel-Crutcher Cloud

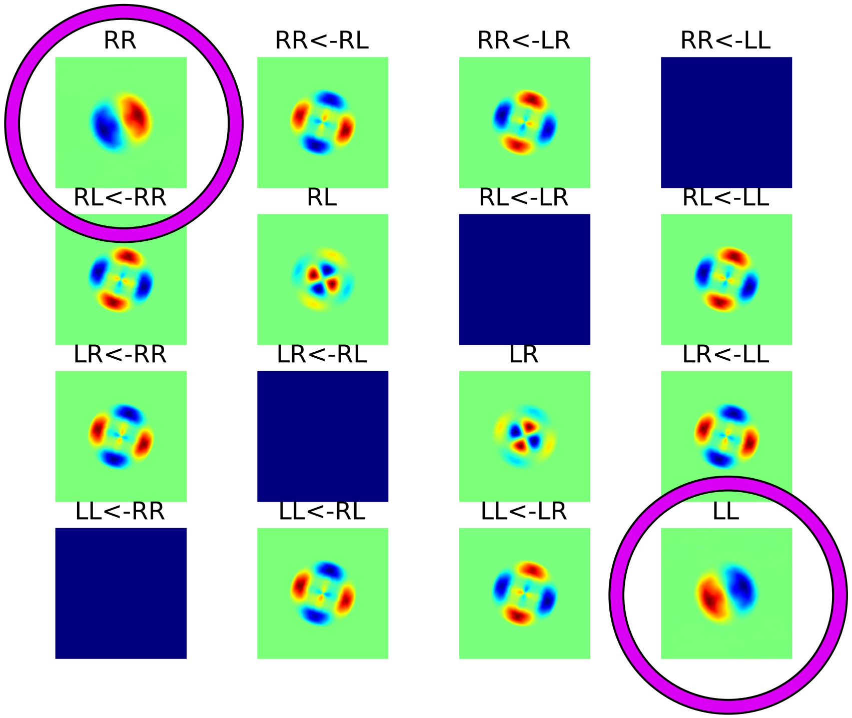


- Prediction: $B > 30\ \mu G$.

JVLA Full Mueller A-Projection

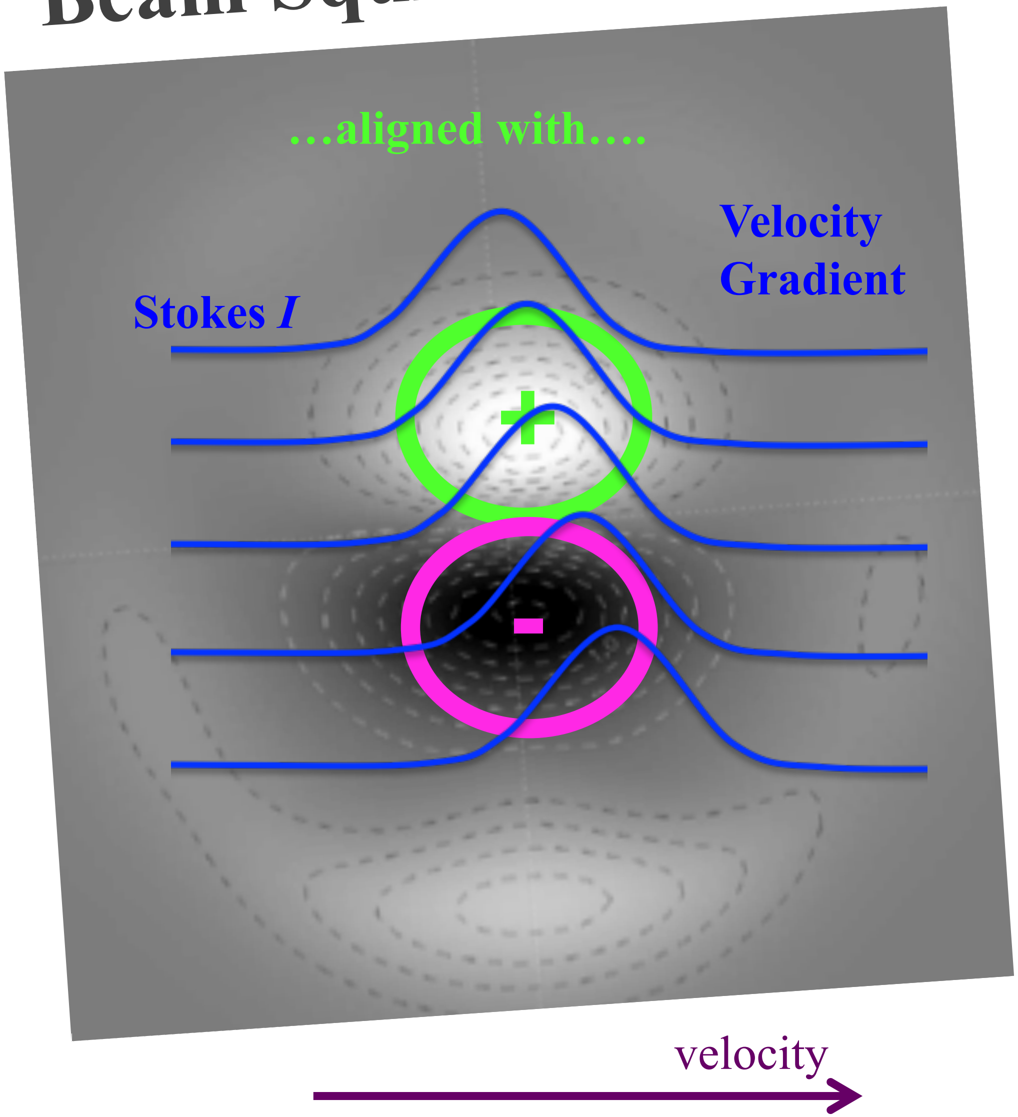


Aperture Real



Aperture Imag

Beam Squint



produces a Stokes *V* response that has the exact signature of Zeeman splitting!

To estimate instrumental contribution we need to know:

(1) Map of beam squint pattern.

(2) Stokes *I* spectral line cube in vicinity of source.

IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. AP-21, NO. 3, MAY 1973

Depolarization Properties of Offset Reflector Antennas

TA-SHING CHU AND R. H. TURRIN

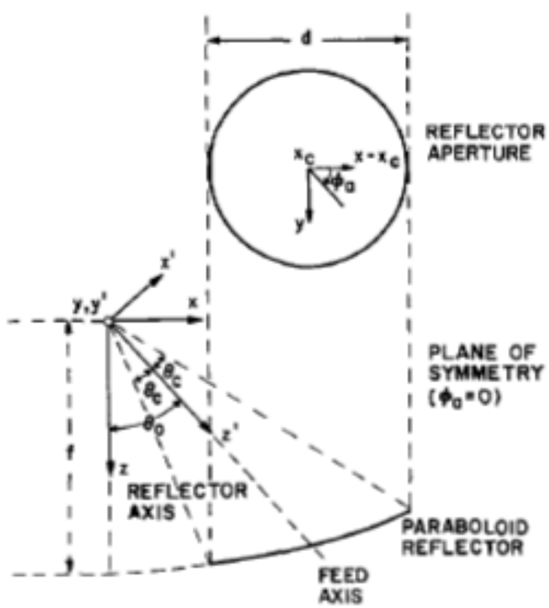


Fig. 1. Geometry of offset reflector.

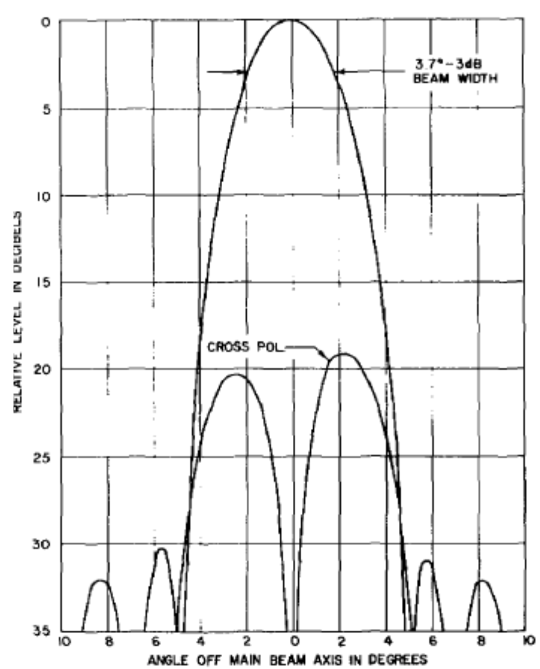


Fig. 6. Measured radiation pattern of offset fed paraboloid antenna linearly polarized at 18.5 GHz. Aperture diameter is 12 in, $f/D = 0.25$.

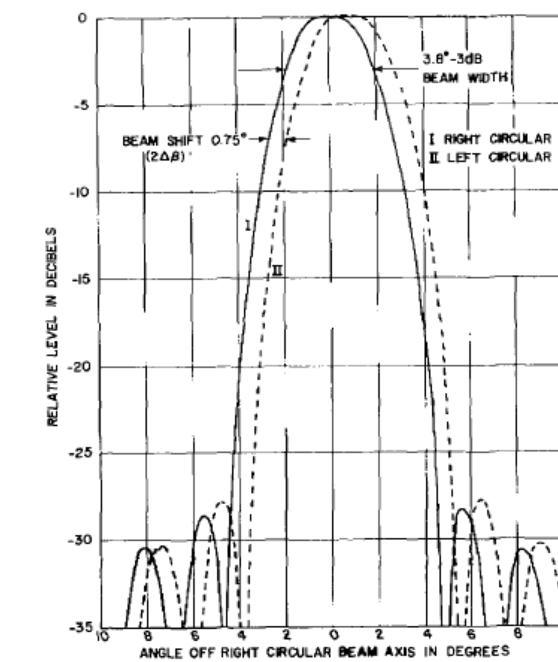


Fig. 7. Measured radiation patterns of offset fed paraboloid antenna with circular polarization at 18.5 GHz. Aperture diameter is 12 in, $f/D = 0.25$.

REFLECTOR ANTENNA DESIGN MEMO SERIES

Germán Cortés M. April 23, 2008

July 14, 2009

Mizugutch or Mizuguchi or Mizusawa Condition minimizes beam squint.

1 Mizusawa's Condition Gregorian Case

Let us use [DeBoer, 2001] notation, and define,

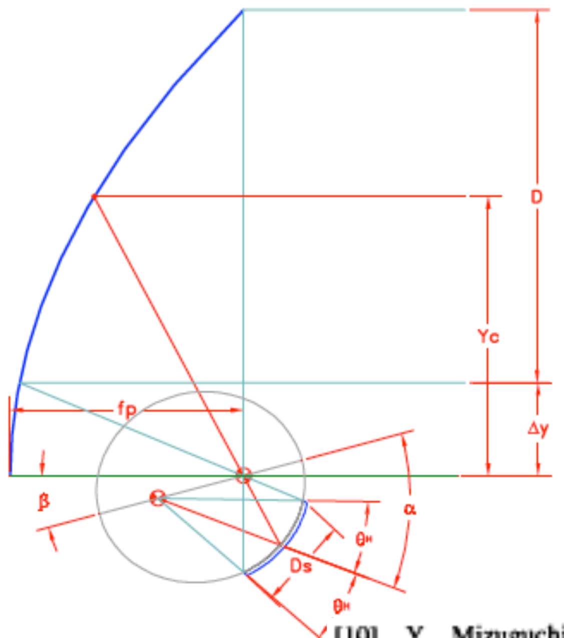
$$\eta = \frac{y_c/D}{f_p/D} \quad (1)$$

$$\xi = 2\frac{f_p}{D}\tan\left(\frac{\theta_H}{2}\right), \quad (2)$$

where f_p is the *parent* paraboloid focal length, D is the main projected aperture, θ_H is the half illumination angle of the sub-reflector from the secondary focus.

Then the offset design may be expressed in terms of the following equations:

$$\alpha = 2\tan^{-1}\left[\frac{1+e}{1-e}\tan\left(\frac{\beta}{2}\right)\right] \quad (3)$$



[10] Y. Mizuguchi, M. Akagawa, and H. Yokoi, "Offset Gregorian antenna," *Trans. IECE Japan*, vol. J61-B, no. 3, pp. 166–173, Mar. 1978.

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[Tanaka and Mizusawa, 1975] H. Tanaka and M. Mizusawa, "Elimination of Cross-Polarization in Offset Dual-Reflector Antennas", *Trans. of I.E.C.E. of Japan* Vol. 58-B, No. 12, pp 643-650, Dec. 1975.

[Mizugutch, 1975] Y. Mizugutch, M. Akaqawa and H. Yokoi, "Offset Dual- Reflector Antenna", *IEEE AP-S Symposium*, Oct., 1976.

[Mizusawa, 1976] M. Mizusawa and T. Katagi: "The Equivalent Parabola of a Multi-reflector Antenna and Its Application", *Mitsubishi Electric Engineer*, 49 Sept., 1976.

Astron. Astrophys. 82, 388 (1980)

ASTRONOMY AND ASTROPHYSICS

- **Diffuse Warm-Ionized Medium**
- **Photodissociation Regions**

Research Note

On the Zeeman Splitting of High *n* Recombination Lines

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Received July 23, 1979

There are 100+ Nα RRL transitions in ngVLA bands!

Summary. Rigorous calculations of the Zeeman splitting of high $n\alpha$ and $n\beta$ lines originating in H II, He II, and C II are reported. The resulting Zeeman pattern is identical with the hydrogen triplet.

Key words: Zeeman splitting – radio recombination lines

In an attempt to explain the observational absence of predicted (Dupree, 1968) high-n solar radio recombination lines, we considered Zeeman broadening and derived as a representative example the corresponding Zeeman pattern for high-$n\alpha$ hydrogen lines (Greve, 1975). In these derivations we assumed equal strength for all fine structure transitions, and summed over groups of transitions in order to obtain a semi-analytical solution of the problem. A similar, though not rigorous derivation (based on the analogy of the splitting of the 21 cm hydrogen line) of the high-n

For high n lines, the Paschen-Back effect (see Herzberg, 1944) needs not be considered since for the majority of the states $M_1 \gg M_s$.

The results of the rigorous calculations can be summarized as follows:

a) for large n (in the calculations $30 \leqq n \leqq 300$) identical hydrogenlike Zeeman triplets (σ_+, σ_-, π) are obtained for the $n\alpha$- and $n\beta$-lines of H II, HeII, C II,

b) for the majority of the states $g = 1$ and sharp (resolution of the calculations $\Delta g = 0.1$) Zeeman components σ_+, σ_-, π of equal strength are obtained,

c) the σ_+, σ_- components are displaced from the π component at the line centre by

$$\Delta\nu_{\sigma+,-} = 1.39 \times 10^6 H\,(\mathrm{s}^{-1}) \tag{1}$$

with H the magnetic field strength in Gauss. The constant in Eq.

Molecular Clouds & Star-Forming Regions in the Milky Way

- Extensive Zeeman work by Momjian, Sarma, Vlemmings, Surcis, Etoka, Crutcher, et al.
  - Thermal OH in molecular clouds.
    - Bourke et al. (2001) suggest single-dish detection rate is low due to fields being beam-averaged.
      - ngVLA gives us resolution and sensitivity to investigate.
  - SiO & H_2O masers in AGB stars and supergiants
  - Protoplanetary nebulae (Etoka & Diamond 2010)
  - Methanol masers in massive SF regions
- CCS in young star-forming cores
- CN in disks and cores

Class I Methanol Masers at 36 & 44 GHz

THE ASTROPHYSICAL JOURNAL, 705:L176–L179, 2009 November 10
doi:10.1088/0004-637X/705/2/L176

DETECTION OF THE ZEEMAN EFFECT IN THE 36 GHz CLASS I CH_3OH MASER LINE WITH THE EVLA

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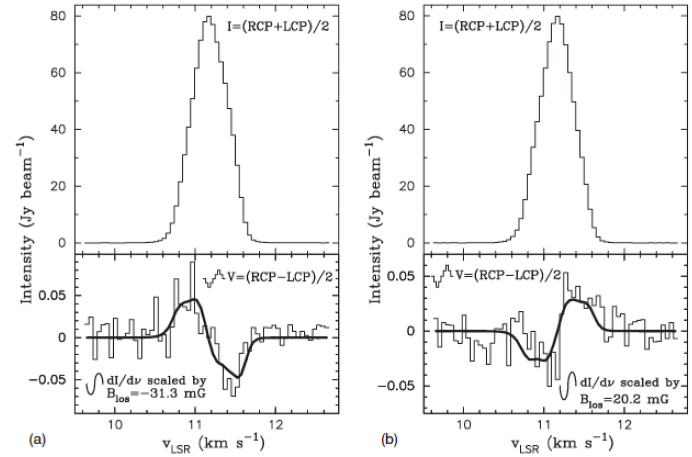
Received 2009 September 9; accepted 2009 October 6; published 2009 October 22



THE ASTROPHYSICAL JOURNAL LETTERS, 730:L5 (4pp), 2011 March 20
doi:10.1088/2041-8205/730/1/L5

DISCOVERY OF THE ZEEMAN EFFECT IN THE 44 GHz CLASS I METHANOL (CH_3OH) MASER LINE

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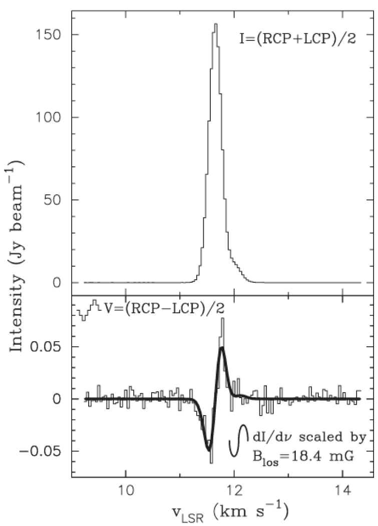
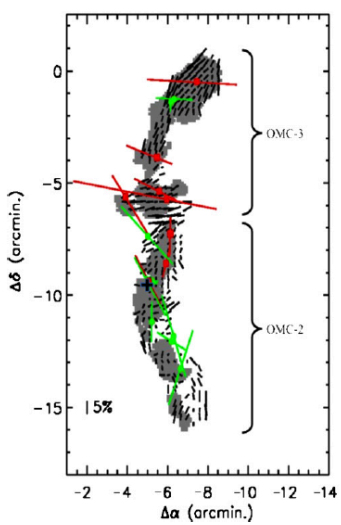
Received 2010 September 15; accepted 2011 February 1; published 2011 February 24





THE ASTROPHYSICAL JOURNAL, 834:168 (6pp), 2017 January 10
doi:10.3847/1538-4357/834/2/168

THE ZEEMAN EFFECT IN THE 44 GHZ CLASS I METHANOL MASER LINE TOWARD DR21(OH)

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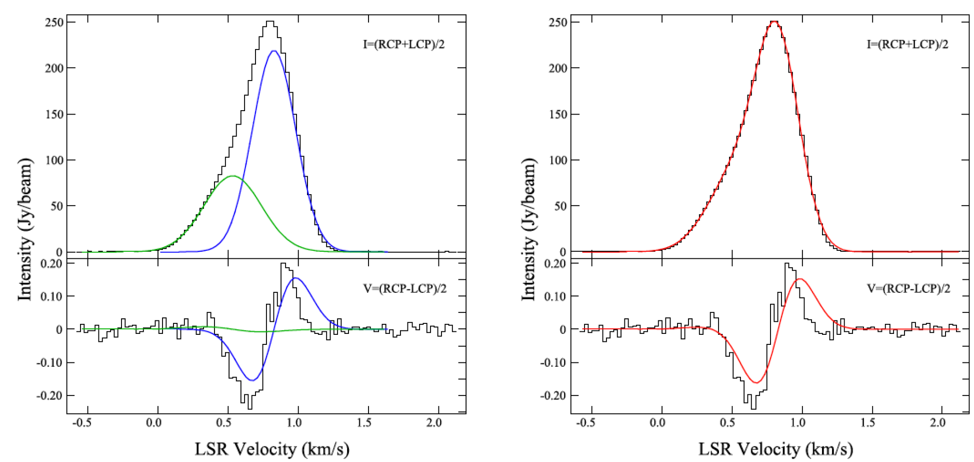
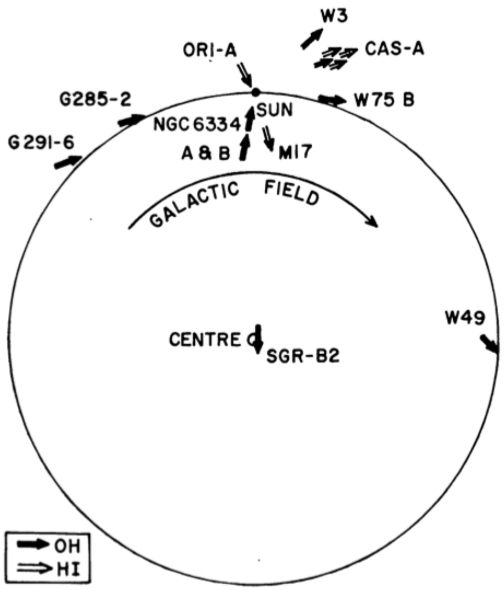
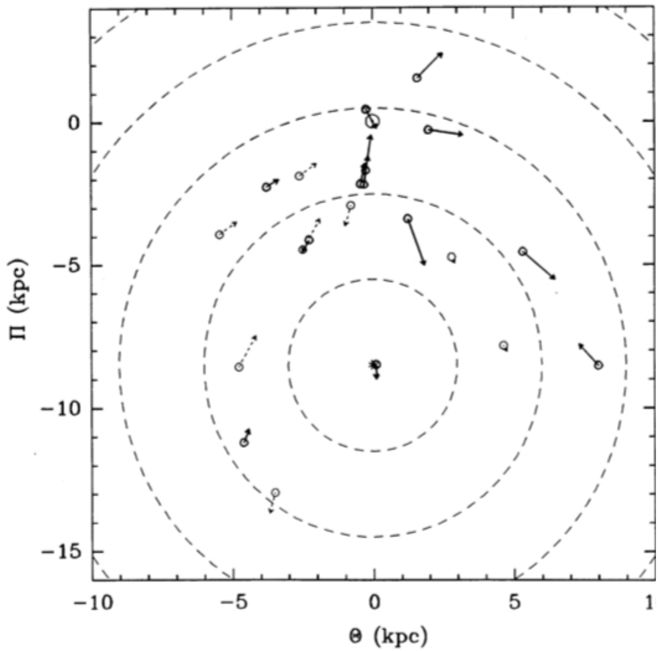


OH Masers in the Milky Way

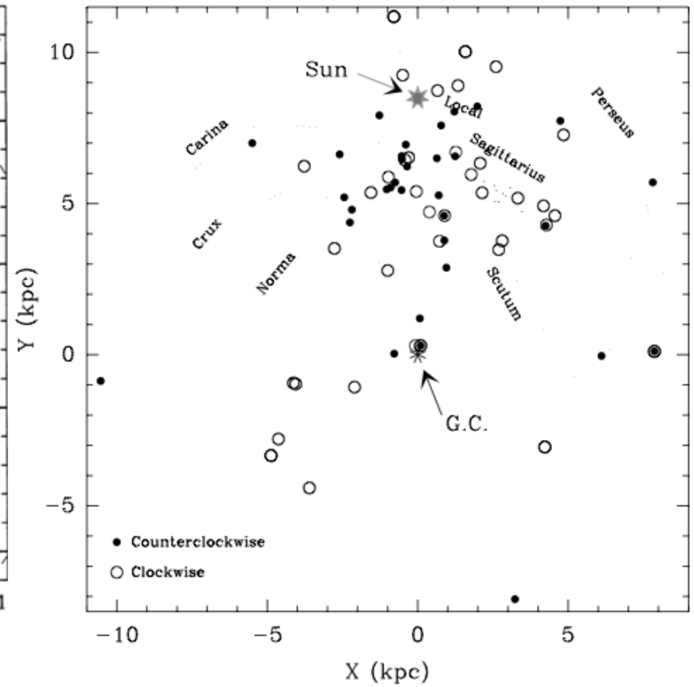
Davies (1974)

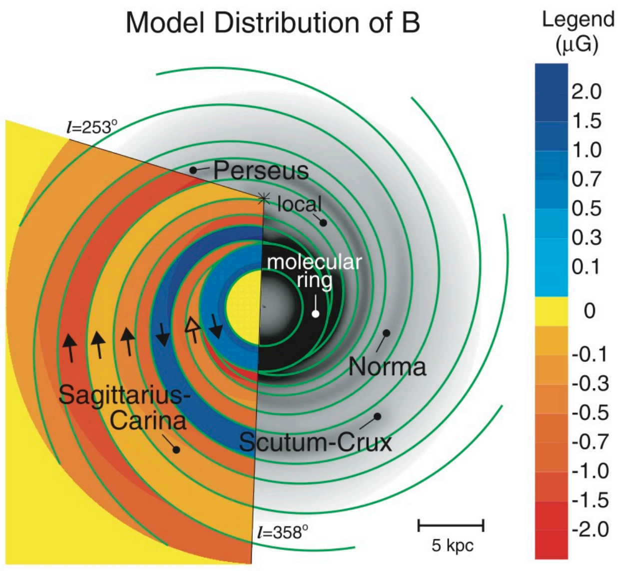


Reid & Silverstein (1990)



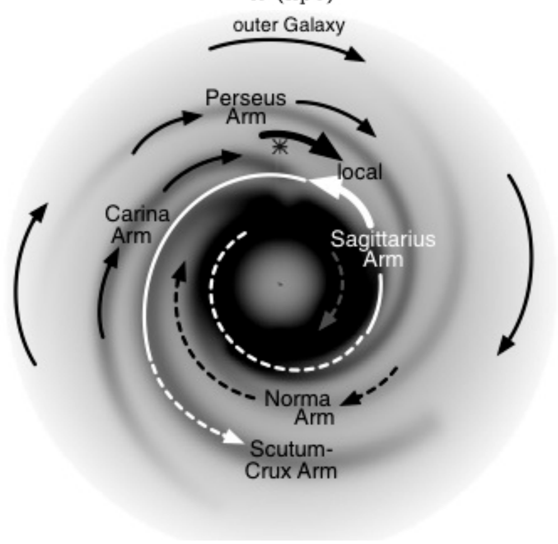
Fish et al. (2003)





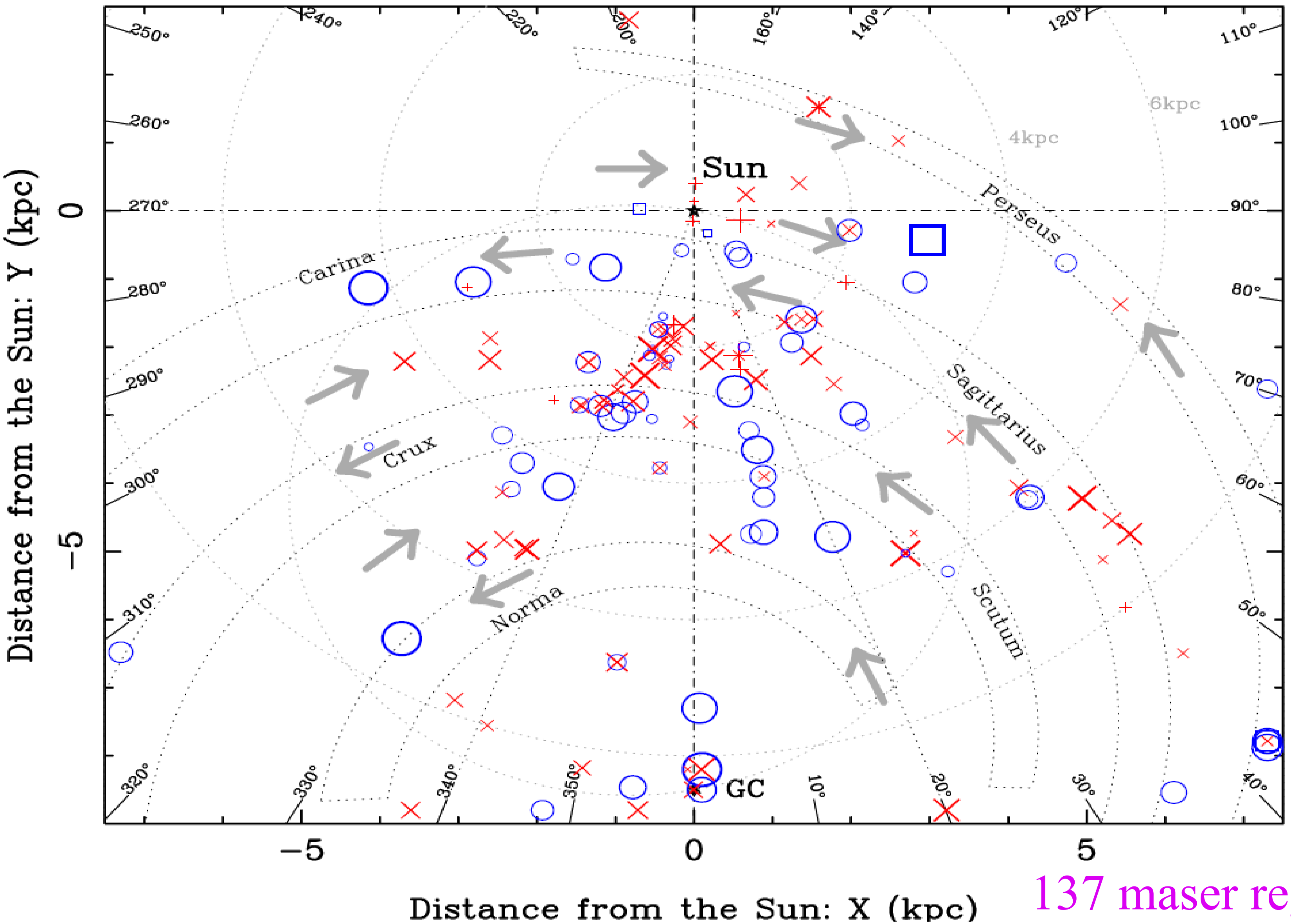
Brown et al. (2007)

Rotation Measures



van Eck et al. (2011)

OH Masers As Tracers of Galactic Field



137 maser regions

Han & Zhang 2007, A&A, 464, 609

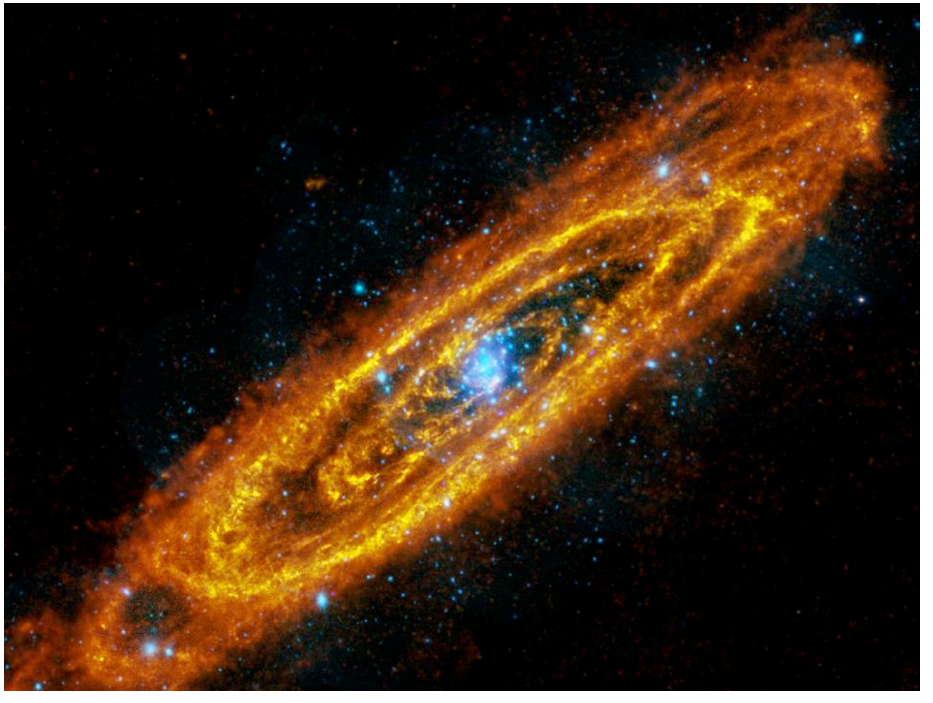
Need more data and better distances.

OH Masers in Nearby Galaxies

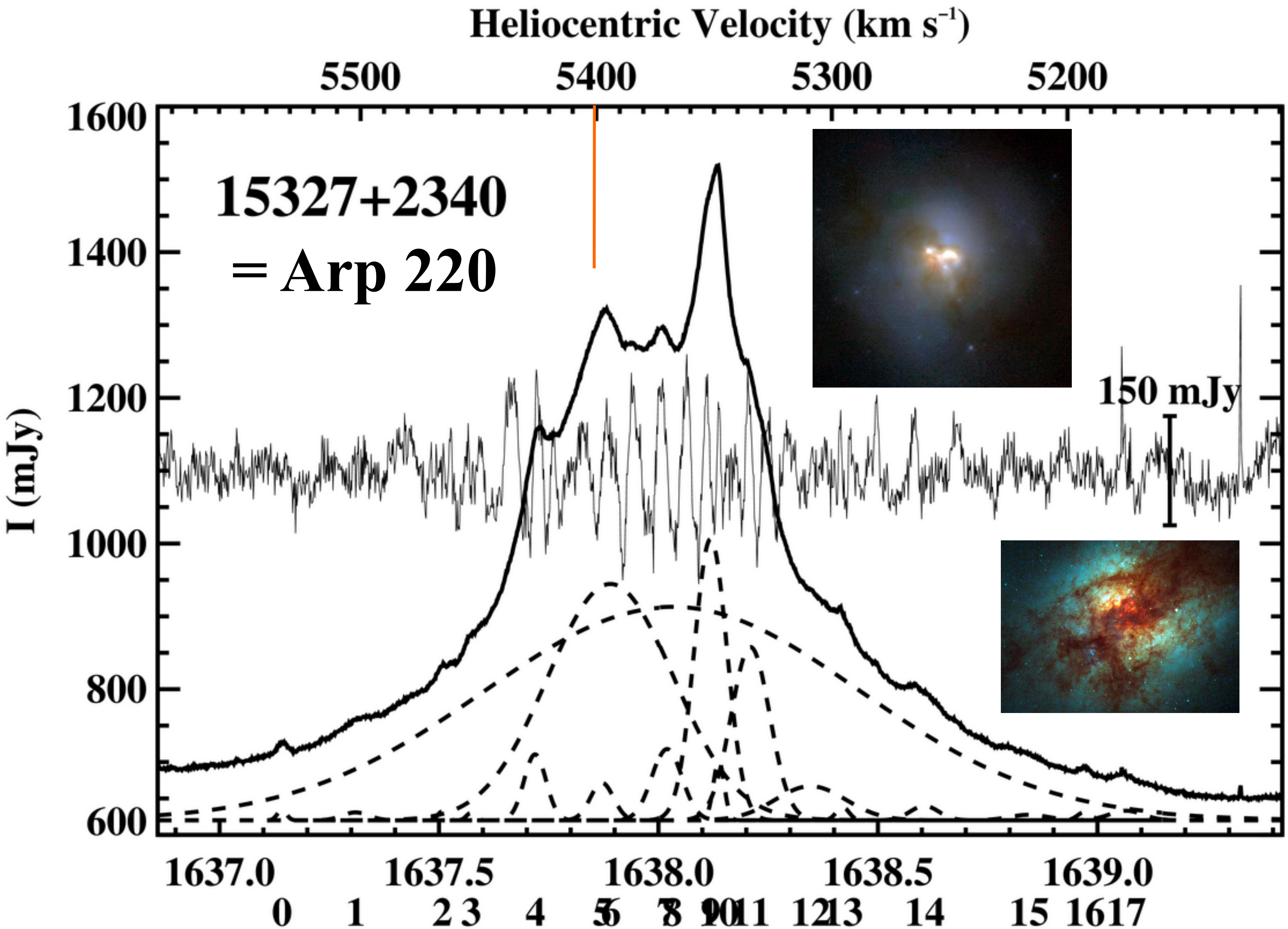
M31

Willett (2012) PhD work with VLA.

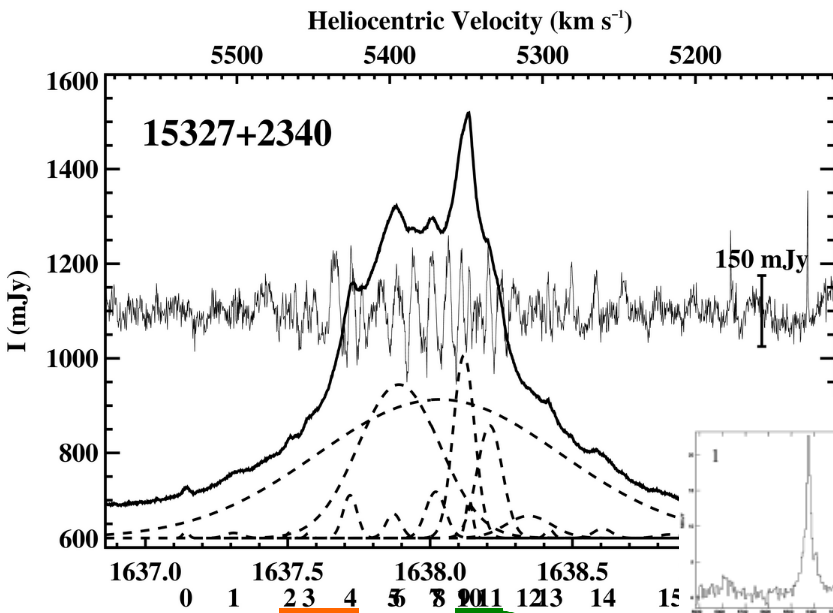
Found no OH masers to >10 mJy limit.



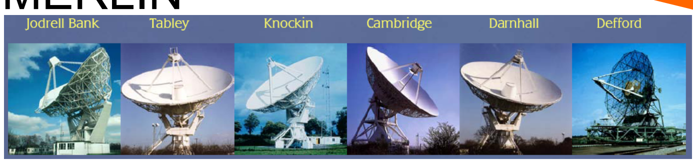
OH Megamasers

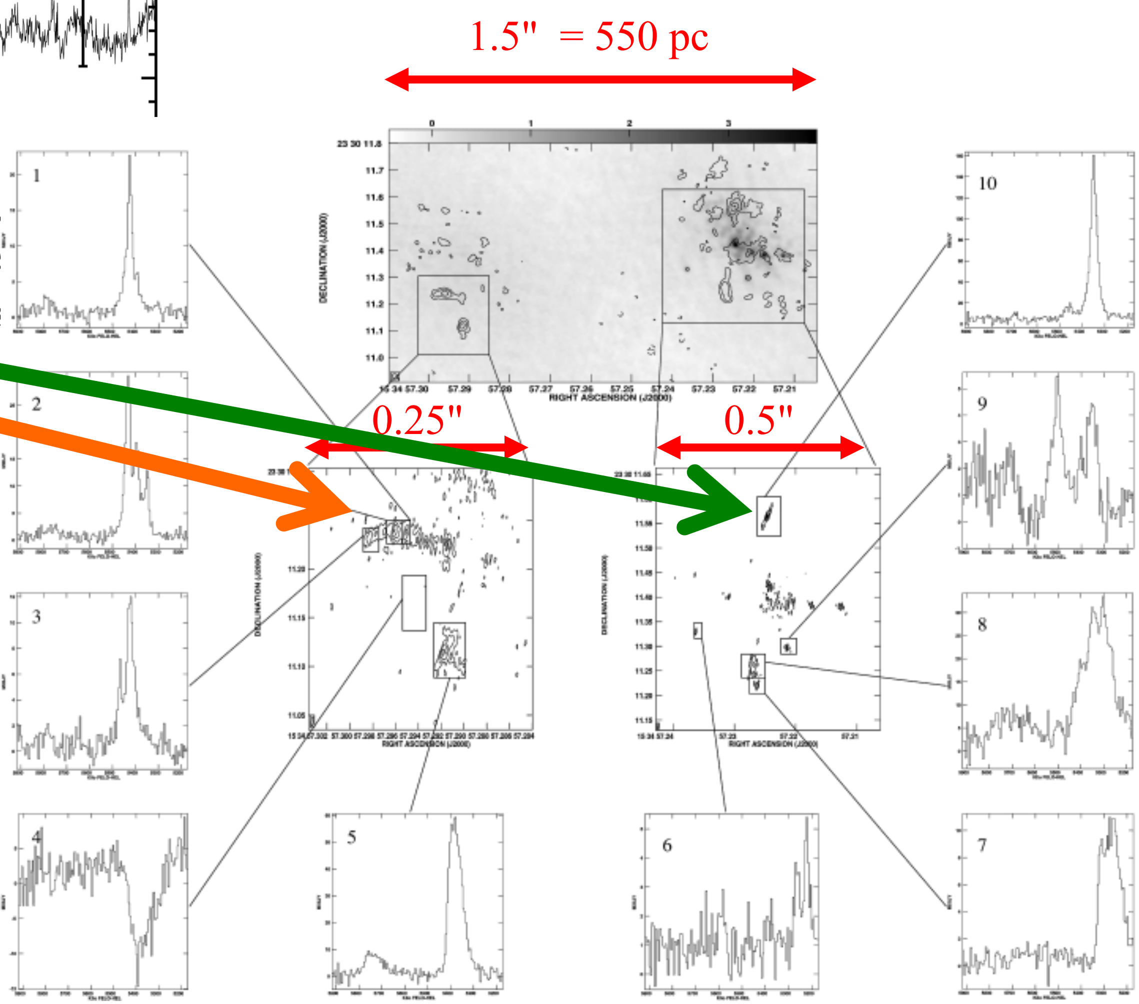


Arp 220



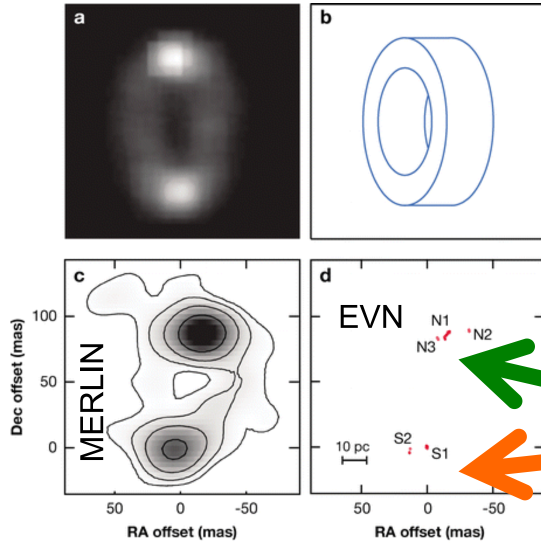
MERLIN





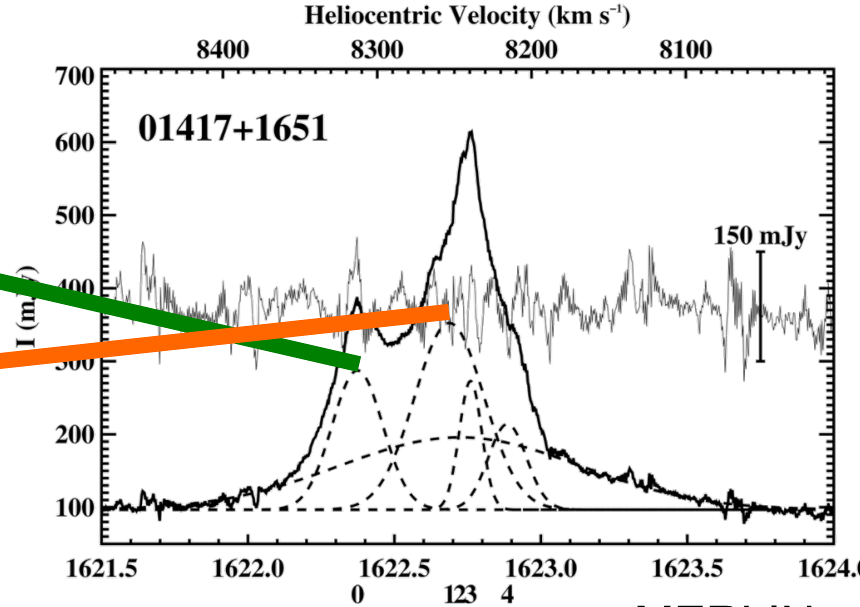
Rovilos, Diamond, Lonsdale[2], & Smith 2003

III Zw 35

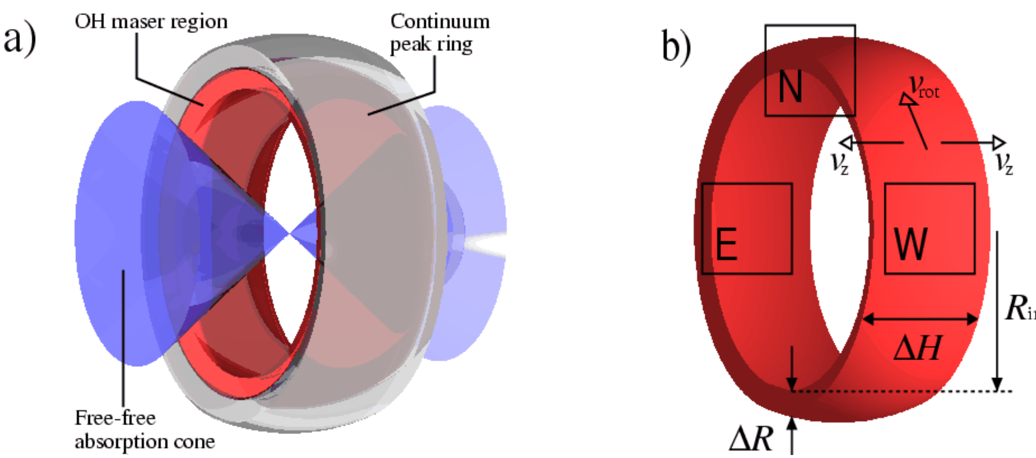


Lo, KY. 2005
Annu. Rev. Astron. Astrophys. 43: 625–76

100 pc

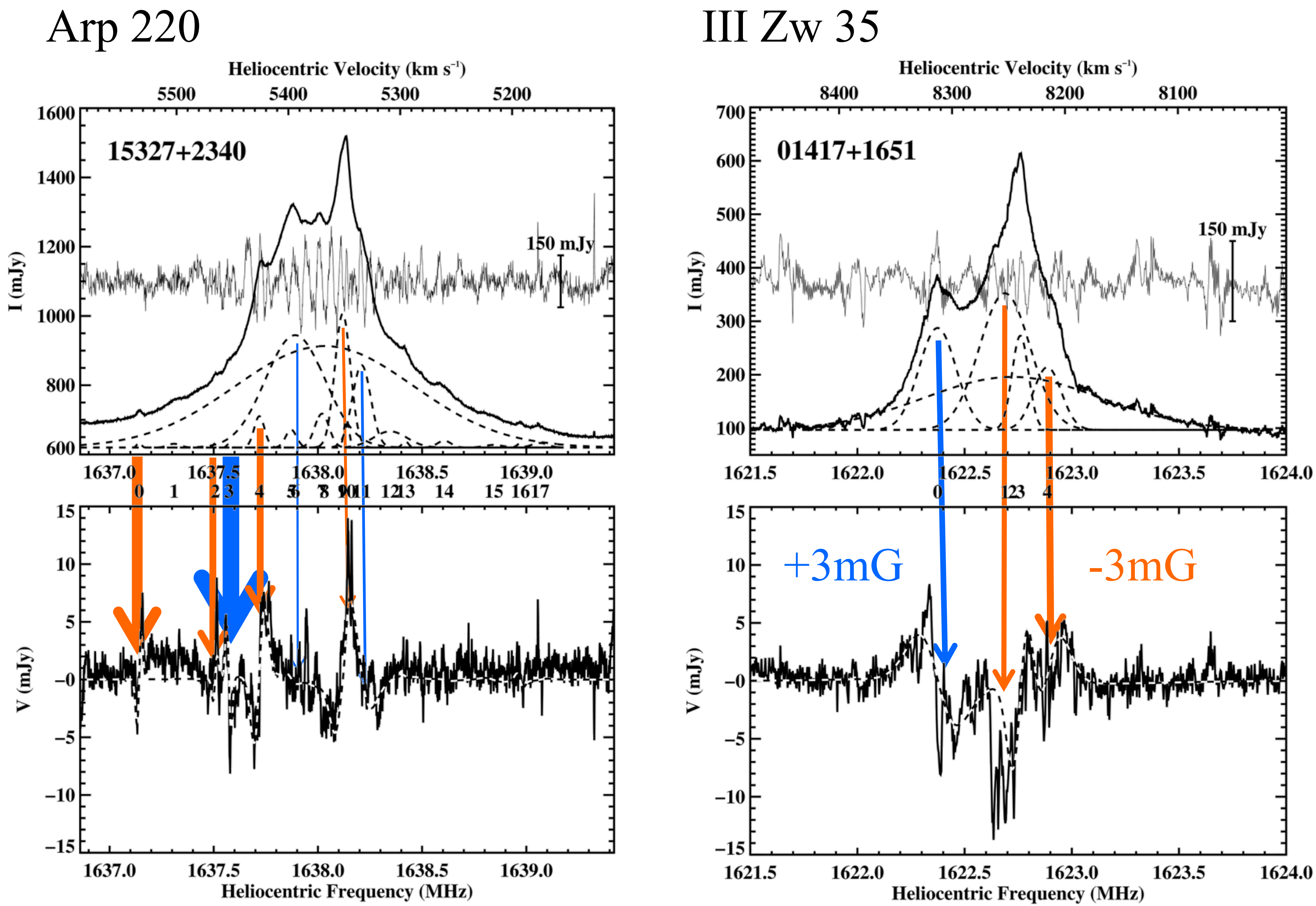


MERLIN



Pihlström, Conway, Booth, Diamond, & Polatidis 2001

Parra, Conway, Elitzur, & Pihlström 2005



Arp 220
III Zw 35
Heliocentric Velocity (km s⁻¹)
15327+2340
01417+1651
150 mJy
I (mJy)
V (mJy)
+3mG
-3mG
Heliocentric Frequency (MHz)

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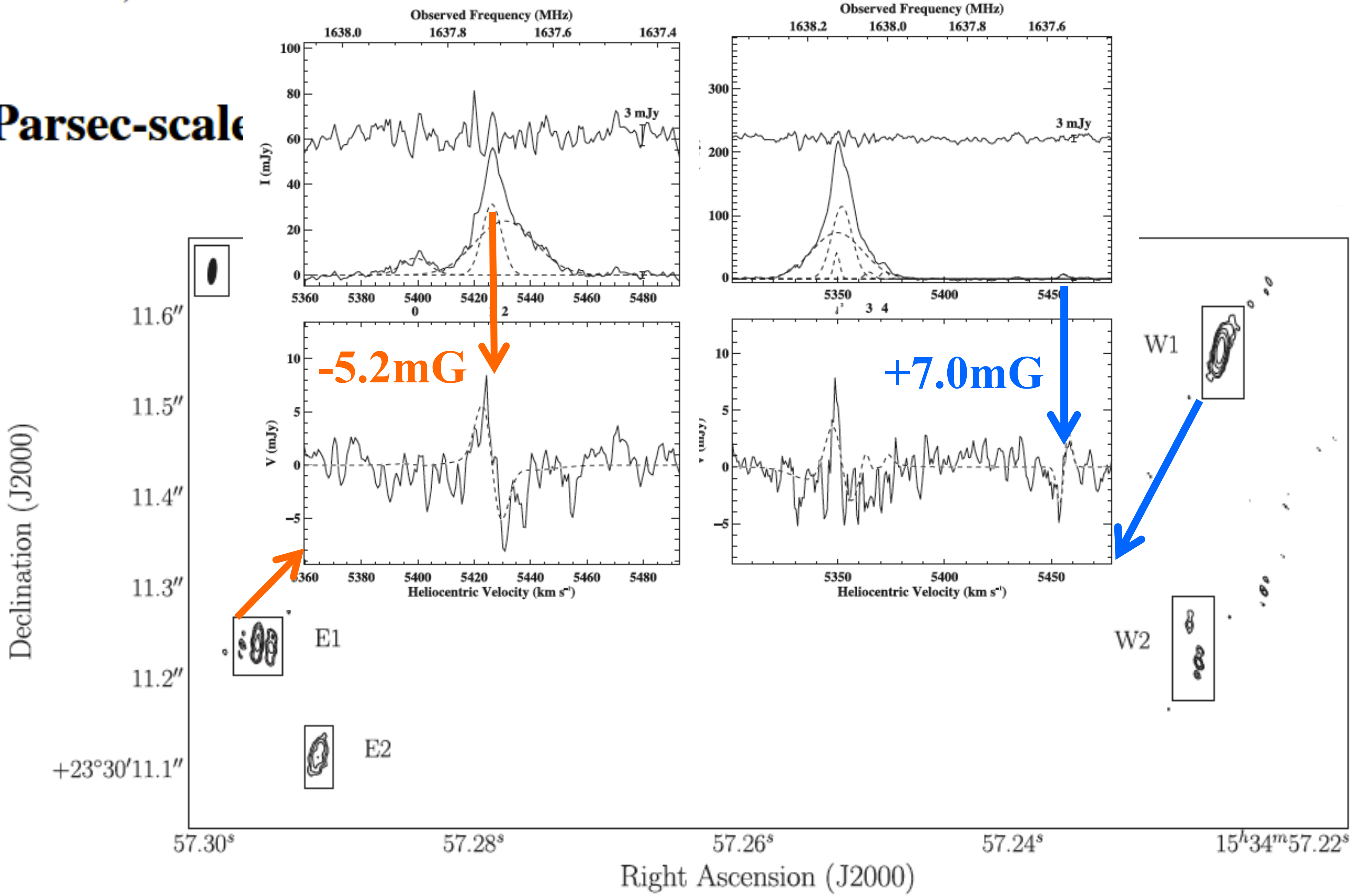
MNRAS 447, 1103–111

doi:10

Parsec-scale



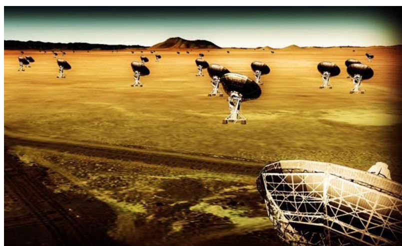
Megamasers

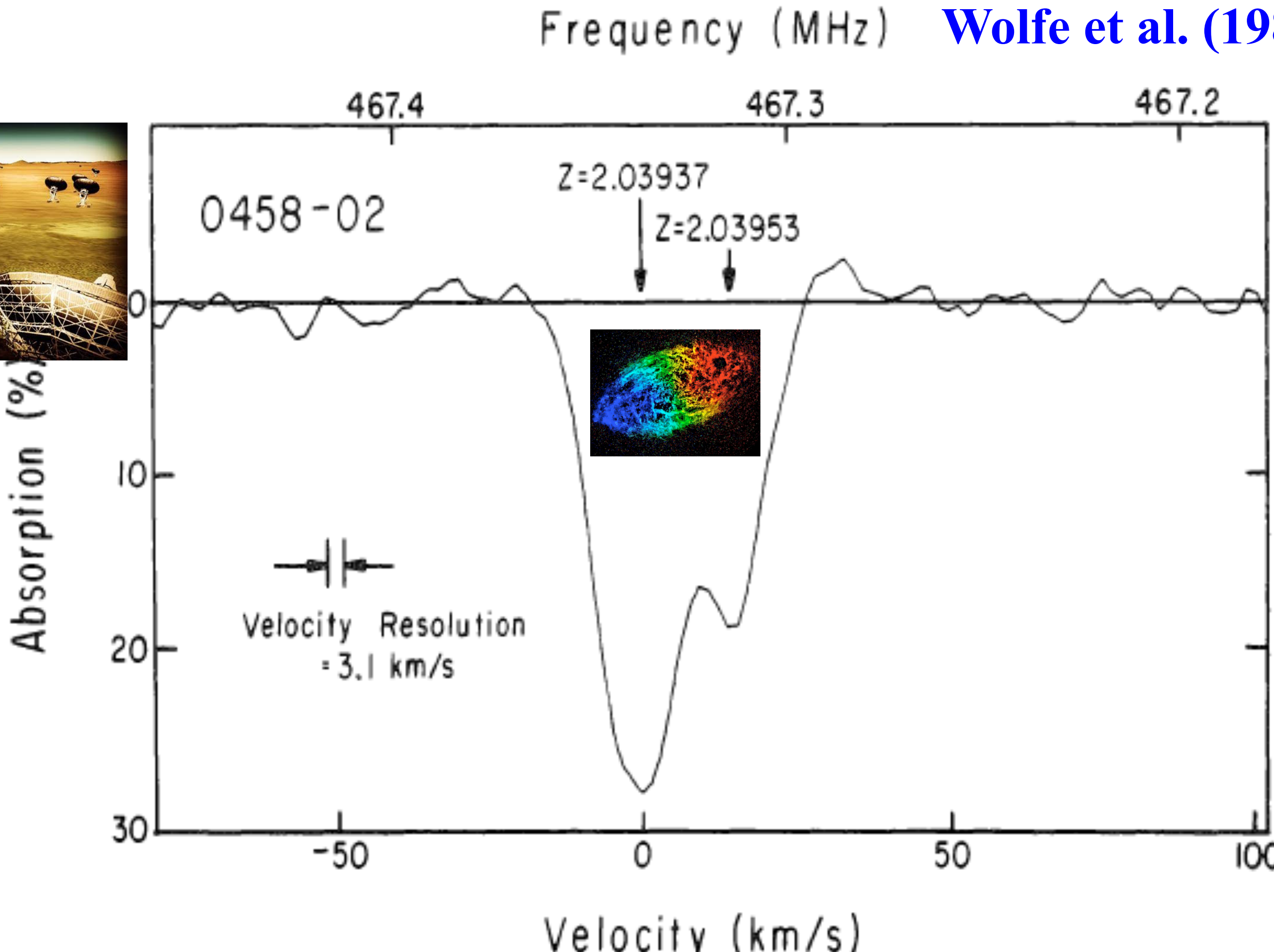
- All 77 OHMs in Arecibo sky have now been observed (McBride & Heiles 2013).
- Fields between 3 and 20 mG.
- 11 galaxies with Zeeman detections.
  - Galaxies show multiple field components.
  - Field reversals.
- ngVLA affords large sky coverage
- ngVLA allows search of H_2O megamasers at 22 GHz

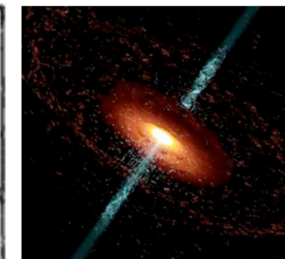
Damped Ly-α Absorbers (DLAs)

QSO PKS 0458 – 02

Wolfe et al. (1985)

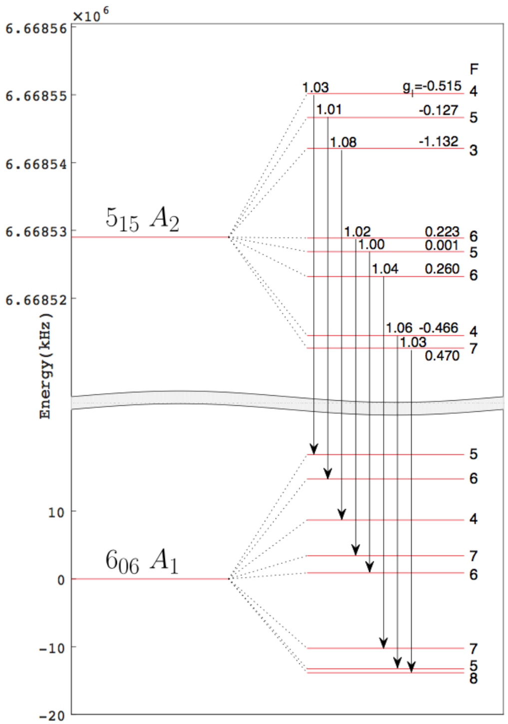


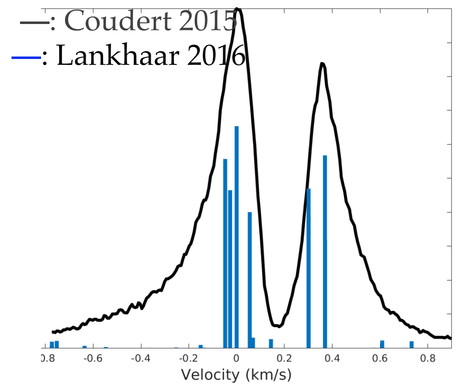




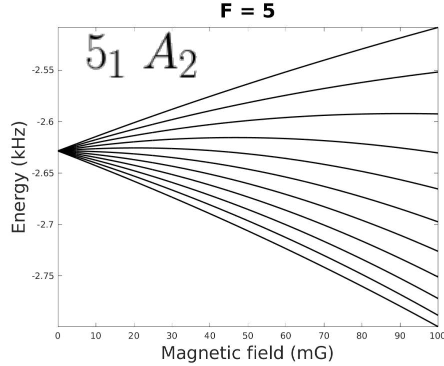
Characterizing Methanol as a Magnetic Field Tracer in Star Forming Regions (Lankhaar et al. 2016 and 2017 [submitted])

Quantum chemical calculations to magnetic field characteristics of methanol





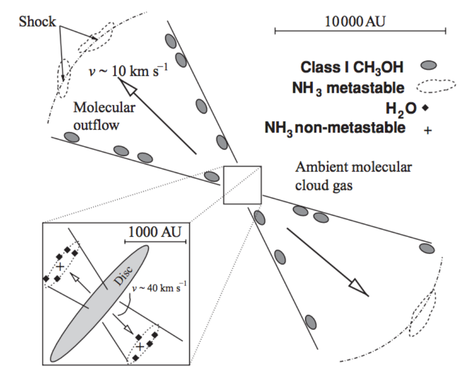
F = 5



Zeeman parameters available for all torsion-rotation transitions

Non-linear effects could also arise in other molecules

Allows for (re-)interpretation of current and coming methanol maser polarization measurements



- Class II: 6.7 GHz (Vlemmings et al. 2005)
  - $\langle|B|\rangle \approx 12$ mG, $n_{H_2} \approx 10^8$ cm^{-3}
  - Implies dynamically important magnetic field!
- Class I: 44 GHz, 36 GHz (Sarma and Momjian 2009, 2011 and 2017)
  - $|B| \approx 20 - 75$ mG, $n_{H_2} \approx 10^8$ cm^{-3}
  - Tracer of the shocked region

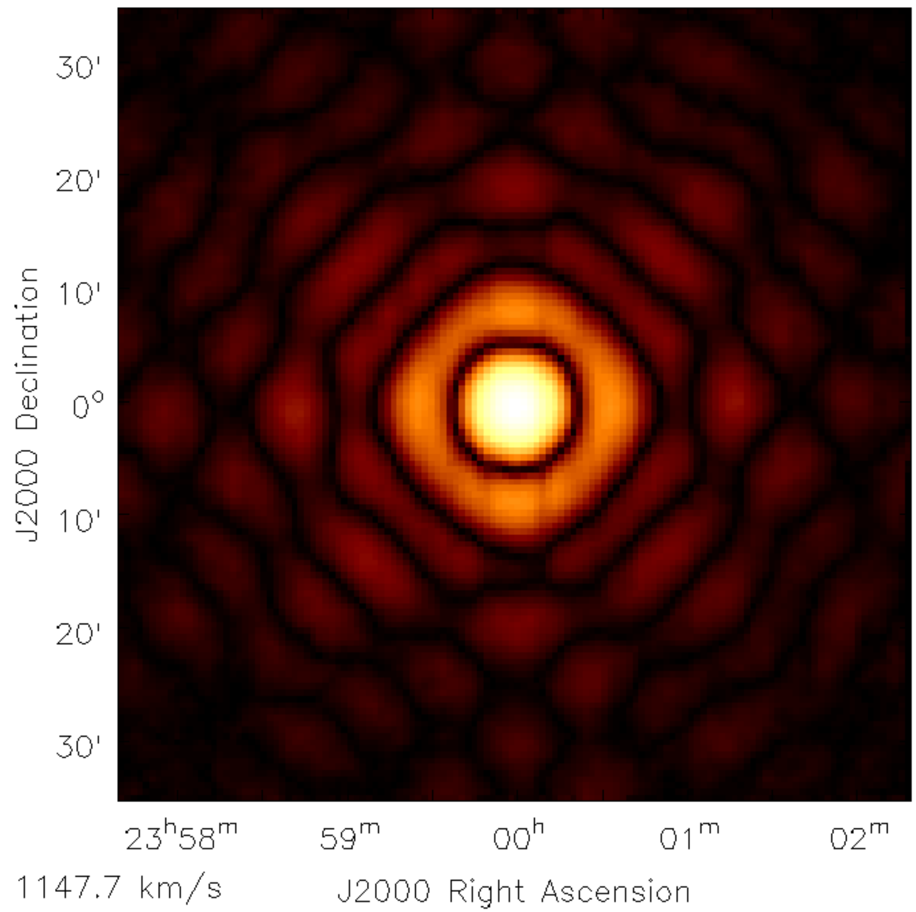
Summary

- Advances in Zeeman effect driven by collecting area, frequency coverage, and clean instrumental polarization.
- Potential Zeeman targets for the ngVLA:
  - HI & OH absorption in the Milky Way
  - Diffuse 21-cm emission in the Milky Way
  - Molecular clouds and star-forming regions
  - OH masers tracing Galactic field structure
  - OH masers in nearby galaxies
  - OH megamasers in starburst galaxies
  - Damped Ly-α absorbers (DLAs)

	1-3 GHz	6-14 GHz	20-40 GHz	65-95 GHz	85-115 GHz	
Table 1: Next Generation VLA notional parameters						
Parameter [units]	**2 GHz**	**10 GHz**	**30 GHz**	**80 GHz**	**100 GHz**	***Notes***
Field of View FWHM [arcmin]	29	5.9	2	0.6	0.51	a
Aperture Efficiency [%]	65	80	75	40	30	
Effective Area, A_{eff}, x 10^4 [m^2]	5.1	6.2	5.9	3.1	2.3	b
System Temp, T_{sys} [K]	29	34	45	70	80	c
Bandwidth [GHz]	2	8	20	30	30	d
Continuum rms, 1 hr [μJy/beam]	0.93	0.45	0.39	0.96	1.48	e
Line rms, 1 hr, 10 km/s [μJy/beam]	221	70	57	100	130	
Resolution FWHM [milli-arcsec]	140	28	9.2	3.5	2.8	f
Brightness Temp (T_B) rms continuum, 1 hr, [K]	14	7	6	15	23	g
Line rms 1 hr, 1" taper, 10 km/s [μJy/beam]	340	140	240	860	-	h
T_B rms line, 1 hr, 1" taper, 10 km/s, [K]	100	1.8	0.32	0.17	-	i

Don’t Let Stokes V Be the Garbage Dump

JVLA holography revealed a rotation in addition to lateral shift in Stokes V beam. Ideas???



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