Tim Robishaw - Dominion Radio Astrophysical Observatory - Canada

Zeeman Splitting of OH Megamasers as a Probe of Magnetic Fields in Starburst Galaxies

The Magnificent Magnetic Mysterium Megamasers!

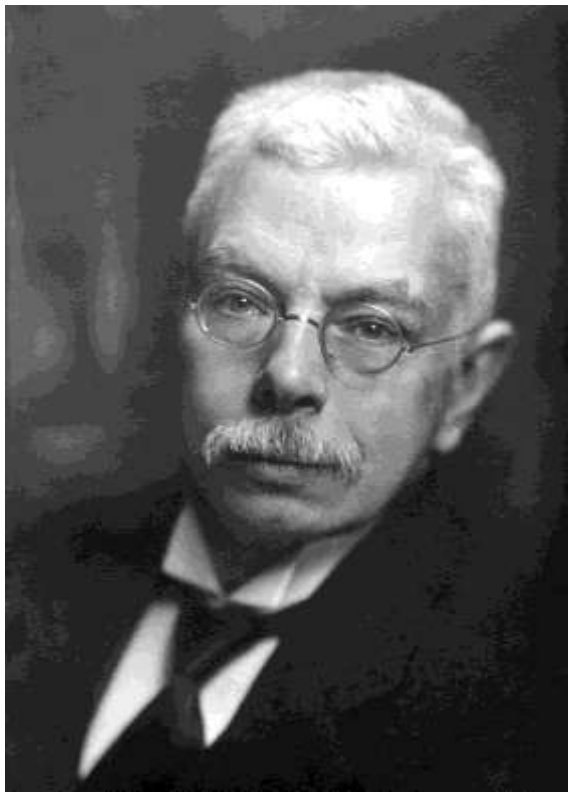


Tim Robishaw

NRC·CNRC Canada

THE
ASTROPHYSICAL JOURNAL
AN INTERNATIONAL REVIEW OF SPECTROSCOPY
AND ASTRONOMICAL PHYSICS

1897
ApJ Vol 5

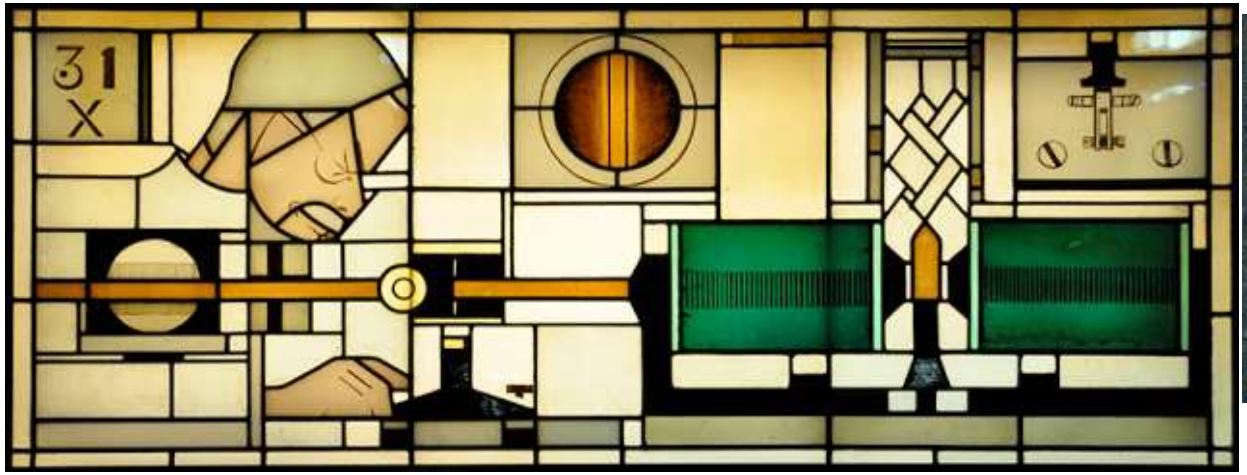


Pieter Zeeman
(1865-1943)

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

By P. ZEEMAN.

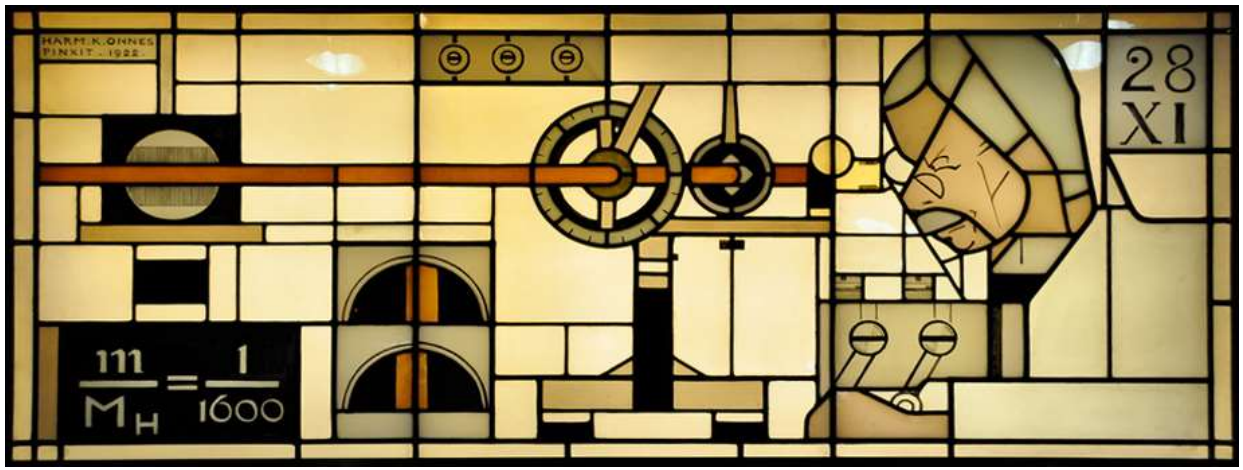
1. SEVERAL years ago, in the course of my measurements concerning the Kerr phenomenon, it occurred to me whether the light of a flame if submitted to the action of magnetism would perhaps undergo any change. The train of reasoning by which I attempted to illustrate to myself the possibility of this is 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.


31
X


NOBELPRIS 1902
FISCHER
ZEEMAN
LORENTZ
SVERIGE 50

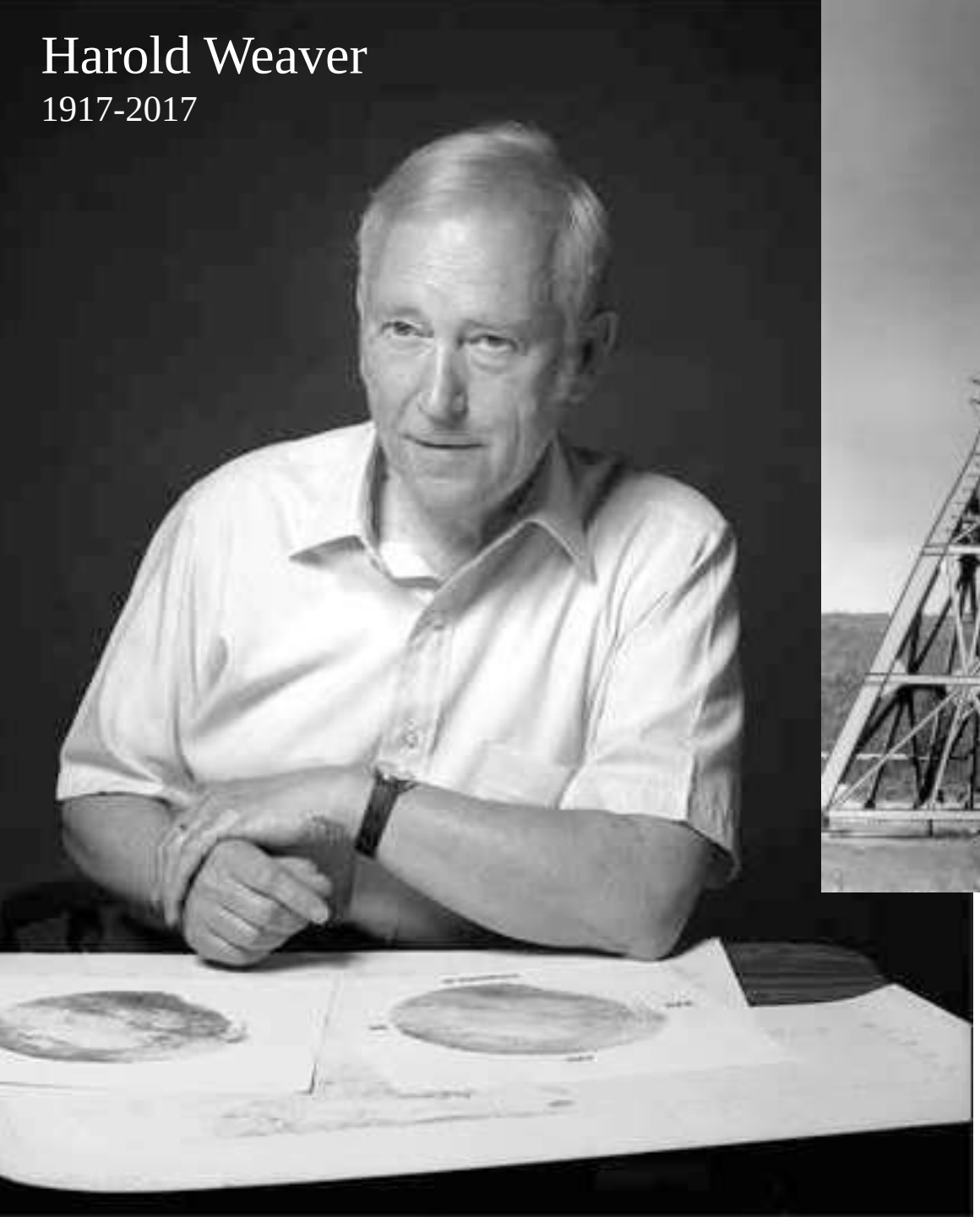

+e
-e
MDCCCXCVI
e
m
V
H
$\pm\frac{1}{2}H\frac{e}{m}$
$\frac{m}{M_H}=?$


KONGLIGA SVENSKA
VETENSKAPS-AKADEMIEN
ALFRED NOBEL
PIETER ZEEMAN


HARM. K. ONNES
PINXIT - 1922
28
XI
$\frac{m}{M_H}=\frac{1}{1600}$


ALFR.
NOBEL

Harold Weaver
1917-2017





Hat Creek, CA
85-ft (26-m)

1965

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

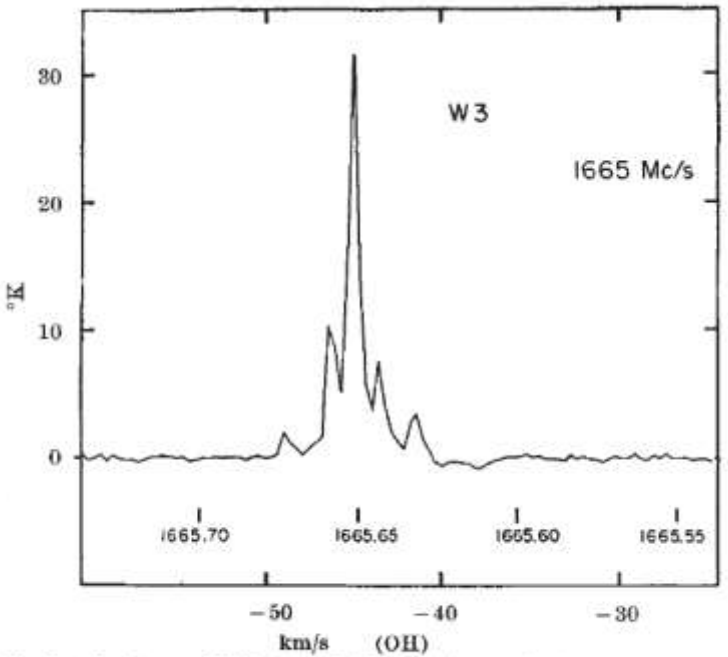


Fig. 2. Spectrum of W3 at 1,665 Mc/s with a resolution of 2 kc/s (0·4 km/sec)

There is no known identification of the strong emission line at 1,665 Mc/s shown in Fig. 1. In what follows, for brevity in writing and to emphasize the surprising nature of the observation just presented, we shall speak of this unidentified line as arising from 'mysterium'.

The form of the spectral lines and extreme narrowness of the emission features is striking. In the 'mysterium' emission there is at least one feature unresolved in the 2 kc/s band-width observations, and therefore not broader than 0·4 km/sec. This is the narrowest line so far observed in the interstellar medium. In a single observing period of a few hours we can see some components of 'mysterium' move from one 2 kc/s channel to another because of the doppler shift caused by the daily rotation of the Earth.

values. In Fig. 3 the intensity of 1,665 exceeds the intensity of 1,667, a situation impossible in thermodynamic equilibrium.



OBSERVATIONS OF POLARIZED OH EMISSION

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



IN a recent article Weaver, Williams, Dieter and Lum[1] reported strong microwave emission lines in the *HII* regions *W3*, *W49*, *W51*, *W75*, *NGC* 6334 and Orion *A* at a frequency of approximately 1,665 Mc/s. In some cases the lines exhibited complex spectral structure, and in all cases the emission at 1,667 Mc/s bore little resemblance in intensity and/or structure to the 1,665 Mc/s emission. In particular, the emission in the region of *W3* was approximately 30° K at 1,665 Mc/s, while no emission was detected at 1,667 Mc/s. Weaver *et al.* concluded that the observations could not be entirely attributed to OH and postulated the existence of an unidentified microwave line which they called "mysterium".

In this article we wish to report observations of emission lines near the source *W3* which reveal that: (*a*) emission is present not only at 1,665 Mc/s but also at 1,667 Mc/s and 1,720 Mc/s with frequency spacings as predicted from the OH molecular spectrum[2]; (*b*) some of the emission at 1,665 Mc/s is linearly polarized by as much as 37 per cent; (*c*) the position of the maximum 1,665 Mc/s emission is displaced from *W3* by approximately 14 min of arc; (*d*) emission features as narrow as 1–1·5 kc/s have been observed. As yet we have not observed other regions. In our opinion, "mysterium" is anomalously excited OH.

The existence of strongly polarized OH emission is both surprising and difficult to explain. Possible polarization mechanisms are: (1) Zeeman effect; (2) Stark effect; (3) resonance scattering; (4) amplification, through a maser-type population inversion, of polarized background radiation. The approximate difference of 90° between the position angles of the −45·2 km/s line and the −43·7 and −49·1 km/s is characteristic of the Zeeman effect when viewed normal to the magnetic field. If the polarization is due to the Zeeman effect, magnetic fields of the order of 5×10^{-3} gauss are indicated. The Zeeman effect is unique among the four mechanisms listed above because it is the only mechanism which will give rise to circular polarization. Therefore, observations of this region with circular polarization are extremely important. Furthermore, if magnetic fields of the order of milligauss are present, 21-cm emission and absorption in the neighbourhood of *W3* should be critically examined.

spectra of Fig. 1. We conclude that an interpretation of our observations in terms of Zeeman splittings of the lines is premature and may ultimately prove to be incorrect.



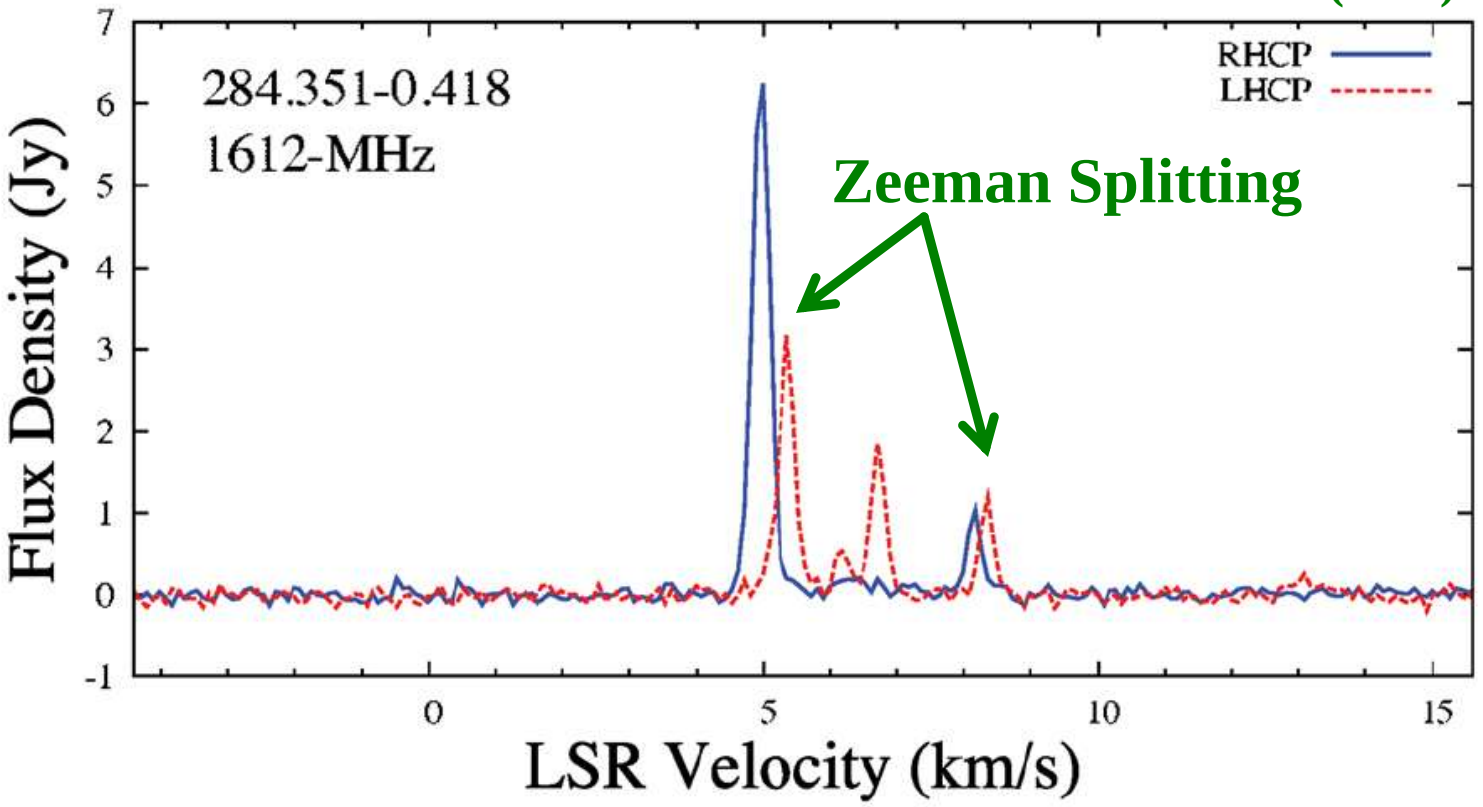


A. H. Barrett
A. E. E. Rogers
Research Laboratory of Electronics,
Massachusetts Institute of Technology,
Cambridge, Massachusetts.

Mysterium was masing Galactic hydroxyl (OH).

- **Main lines at 1665 & 1667 MHz.**
- **Satellite lines at 1612 & 1720 MHz.**
- **In the Milky Way, usually see:**
  - **I(1665)/I(1667) > 1**
  - **FWHM < 1 km/s**

Green et al. (2012)



Mysterium was masing Galactic hydroxyl (OH).

- **Main lines at 1665 & 1667 MHz.**
- **Satellite lines at 1612 & 1720 MHz.**
- **In the Milky Way, usually see:**
  - **I(1665)/I(1667) > 1**
  - **FWHM < 1 km/s**

Some galaxies far, far away have **OH MEGAMASERS**!



A SEARCH FOR OH MEGAMASERS AT $z > 0.1$. I. PRELIMINARY RESULTS

JEREMY DARLING AND RICCARDO GIOVANELLI
Department of Astronomy, Cornell University, Ithaca, NY 14853; darling@astrosun.tn.cornell.edu; riccardo@astrosun.tn.cornell.edu
Received 1999 December 8; accepted 2000 March 7

A SEARCH FOR OH MEGAMASERS AT $z > 0.1$. II. FURTHER RESULTS

JEREMY DARLING AND RICCARDO GIOVANELLI
Department of Astronomy and National Astronomy and Ionosphere Center, Cornell University, Ithaca, NY 14853; darling@astrosun.tn.cornell.edu; riccardo@astrosun.tn.cornell.edu
Received 2000 October 20; accepted 2000 December 6

A SEARCH FOR OH MEGAMASERS AT $z > 0.1$. III. THE COMPLETE SURVEY

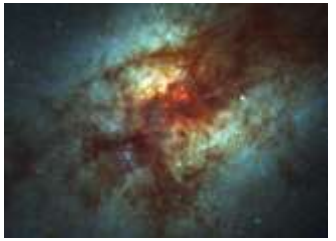
JEREMY DARLING AND RICCARDO GIOVANELLI
Department of Astronomy and National Astronomy and Ionosphere Center, 518 Space Sciences, Cornell University, Ithaca, NY 14853; darling@astro.cornell.edu, riccardo@astro.cornell.edu
Received 2001 December 6; accepted 2002 April 10

Arp 220

First OHM ever detected at Arecibo by Willem Baan in Jan 1982.







Mysterium was masing Galactic hydroxyl (OH).

- **Main lines at 1665 & 1667 MHz.**
- **Satellite lines at 1612 & 1720 MHz.**
- **In the Milky Way, usually see:**
  - **I(1665)/I(1667) > 1**
  - **FWHM < 1 km/s**

Some galaxies far, far away have **OH MEGAMASERS**!

- **$L_{OH}/L_{\odot}=10^{1-4}$**
  - **100 million times L_{OH} of Galactic OH masers!**
  - **Found only in (U)LIRGs ($L_{FIR}/L_{\odot}>10^{12}$)**
    - **Powered by starbursts or AGN.**
    - **Observed out past z ~ 0.20.**
- **Emission primarily in 1667 MHz line.**
  - **1665 MHz emission is either weaker or absent.**
  - **Hardly any 1612 or 1720 MHz satellite lines.**
- **Extremely rare: ~125 known OHMs**

THE ASTROPHYSICAL JOURNAL, 677:985–992, 2008 April 20
© 2008. The American Astronomical Society. All rights reserved. Printed in U.S.A.

THE EFFECT OF 53 μm IR RADIATION ON 18 cm OH MEGAMASER EMISSION

PHILIP LOCKETT[1] AND MOSHE ELITZUR[2]
Received 2007 October 5; accepted 2008 January 9

ABSTRACT

OH megamasers (OHMs) emit primarily in the main lines at 1667 and 1665 MHz and differ from their Galactic counterparts due to their immense luminosities, large line widths, and 1667/1665 MHz flux ratios, which are always greater than 1. We find that these maser properties result from strong 53 μm radiative pumping combined with line overlap effects caused by turbulent line widths $\sim$20 km s^{-1}; pumping calculations that do not include line overlap are unreliable. A minimum dust temperature of $\sim$45 K is needed for inversion, and maximum maser efficiency occurs for dust temperatures $\sim$80–140 K. We find that warmer dust can support inversion at lower IR luminosities, in agreement with observations. Our results are in good agreement with a clumpy model of OHMs, with clouds sizes $\lesssim$1 pc and OH column densities $\sim 5 \times 10^{16}$ cm^{-2}, that is able to explain both the diffuse and compact emission observed for OHMs. We suggest that *all* OH main-line masers may be pumped by far-IR radiation, with the major differences between OHMs and Galactic OH masers caused by differences in line width produced by line overlap. Small Galactic maser line widths tend to produce stronger 1665 MHz emission. The large OHM line widths lead to inverted ground-state transitions having approximately the same excitation temperature, producing 1667/1665 MHz flux ratios greater than 1 and weak satellite line emission. Finally, the small observed ratio of pumping radiation to dense molecular gas, as traced by HCN and HCO$^+$, is a possible reason for the lack of OH megamaser emission in NGC 6240.

Model accounts for 1612 & 1720 MHz satellite lines being significantly weaker than 1667 MHz line…

Now observationally confirmed for all Arecibo-observed OHMs.

THE ASTROPHYSICAL JOURNAL, 645:186–198, 2006 July 1
© 2006. The American Astronomical Society. All rights reserved. Printed in U.S.A.

ULIRGs should have $B \sim 1$ mG to 10 mG

MAGNETIC FIELDS IN STARBURST GALAXIES AND THE ORIGIN OF THE FIR-RADIO CORRELATION

TODD A. THOMPSON,[1,2] ELIOT QUATAERT,[3] ELI WAXMAN,[4] NORMAN MURRAY,[5,6] AND CRYSTAL L. MARTIN[7]

Received 2006 January 26; accepted 2006 March 7

ABSTRACT

We estimate minimum energy magnetic fields ($B_{\rm min}$) for a sample of galaxies with measured gas surface densities, spanning more than four orders of magnitude in surface density, from normal spirals to luminous starbursts. We show that the ratio of the minimum energy magnetic pressure to the total pressure in the ISM decreases substantially with increasing surface density. For the ultraluminous infrared galaxy Arp 220, this ratio is $\sim 10^{-4}$. Therefore, if the minimum energy estimate is applicable, magnetic fields in starbursts are dynamically weak compared to gravity, in contrast to normal star-forming spiral galaxies. We argue, however, that rapid cooling of relativistic electrons in starbursts invalidates the minimum energy estimate. We assess a number of independent constraints on the magnetic field strength in starburst galaxies. In particular, we argue that the existence of the FIR-radio correlation implies that the synchrotron cooling timescale for cosmic-ray electrons is much shorter than their escape time from the galactic disk; this in turn implies that the true magnetic field in starbursts is significantly larger than $B_{\rm min}$. The strongest argument *against* such large fields is that one might expect starbursts to have steep radio spectra indicative of strong synchrotron cooling, which is not observed. However, we show that ionization and bremsstrahlung losses can flatten the nonthermal spectra of starburst galaxies even in the presence of rapid cooling, providing much better agreement with observed spectra. We further demonstrate that ionization and bremsstrahlung losses are likely to be important in shaping the radio spectra of most starbursts at GHz frequencies, thereby preserving the linearity of the FIR-radio correlation. We thus conclude that magnetic fields in starbursts are significantly larger than $B_{\rm min}$. We highlight several observations that can test this conclusion.

All OH MEGAMASERS are found in ULIRGs!!!

with *GLAST*. (3) Zeeman measurements of starbursts can directly probe the magnetic field strength in the dense phase of the ISM, and distinguish between $B \sim B_{\rm min}$ and $B \gg B_{\rm min}$. Existing upper limits in four ULIRGs from Killeen et al. (1996) are above $B_{\rm min}$, but below the equipartition field (§ 3.1). (4) If $B \gg B_{\rm min}$, IC

SPLITTING COEFFICIENTS FOR ZEEMAN TRANSITIONS

Species	Transition	ν (GHz)	b (Hz μG^{-1})	Ref.
Atomic Transitions				
H I.....	$^2S_{1/2}, F = 1$–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				
CH.....	$^2\Pi_{3/2}, J = 3/2, F = 2$–2	0.701677	1.96	1
CH.....	$^2\Pi_{3/2}, J = 3/2, F = 1$–1	0.724788	3.27	1
OH	$^2\Pi_{3/2}, J = 3/2, F = 1$–2	1.6122	1.308	1
OH	$^2\Pi_{3/2}, J = 3/2, F = 1$–1	1.6654	3.270	1
OH	$^2\Pi_{3/2}, J = 3/2, F = 2$–2	1.6673	1.964	1
OH	$^2\Pi_{3/2}, J = 5/2, F = 2$–1	1.7205	1.308	1
OH	$^2\Pi_{3/2}, J = 5/2, F = 2$–3	6.0167	0.678	1
OH	$^2\Pi_{3/2}, J = 5/2, F = 2$–2	6.0307	1.582	1
OH	$^2\Pi_{3/2}, J = 5/2, F = 3$–3	6.0350	1.132	1
OH	$^2\Pi_{3/2}, J = 5/2, F = 3$–2	6.0490	0.678	1
CH_3OH	$J_N = 5_1$–$6_0 A^+$	6.668512	0.0011	8
C_4H.....	$N = 1$–0, $J = 3/2$–1/2, $F = 0$–1	9.493061	−2.457	3
C_4H.....	$N = 1$–0, $J = 3/2$–1/2, $F = 1$–2	9.497616	0.897	3
CCS	$J_N = 1_0$–0_1	11.119446	0.813	5
SO.....	$J_N = 1_2$–1_1	13.044000	1.93	6
OH	$^2\Pi_{3/2}, J = 7/2, F = 3^+$–$3^-$	13.434637	1.06	4
OH	$^2\Pi_{3/2}, J = 7/2, F = 4^+$–$4^-$	13.441417	0.795	4
C_4H.....	$N = 2$–1, $J = 5/2$–3/2, $F = 1$–2	19.014720	1.30	1
C_4H.....	$N = 2$–1, $J = 5/2$–3/2, $F = 2$–3	19.015144	0.93	1
CCS	$J_N = 2_1$–1_0	22.344033	0.767	5
SO.....	$J_N = 1_0$–0_1	30.001630	1.740	5
CCS	$J_N = 3_2$–2_1	33.751374	0.702	5
CCS	$J_N = 4_3$–3_2	45.379033	0.629	5
SO.....	$J_N = 2_1$–1_0	62.931731	1.379	5
SO.....	$J_N = 2_2$–1_1	86.094	0.47	1
C_2H.....	$N = 1$–0, $J = 3/2$–1/2, $F = 2$–1	87.316925	1.40	1
SO.....	$J_N = 3_2$–2_1	99.299875	1.043	5
CN.....	$N = 1$–0, $J = 1/2$, $F = 1/2$–3/2	113.14434	2.18	7
CN.....	$N = 1$–0, $J = 1/2$, $F = 3/2$–1/2	113.17087	−0.31	7
CN.....	$N = 1$–0, $J = 1/2$, $F = 3/2$–3/2	113.19133	0.62	7
CN.....	$N = 1$–0, $J = 3/2$–1/2, $F = 3/2$–1/2	113.48839	2.18	7
CN.....	$N = 1$–0, $J = 3/2$–1/2, $F = 5/2$–3/2	113.49115	0.56	7
CN.....	$N = 1$–0, $J = 3/2$–1/2, $F = 1/2$–1/2	113.49972	0.62	7
CN.....	$N = 1$–0, $J = 3/2$–1/2, $F = 3/2$–3/2	113.59972	1.62	7
SO.....	$J_N = 4_3$–3_2	138.178548	0.800	5
SO.....	$J_N = 5_4$–4_3	178.605168	0.634	5
CN.....	$N = 2$–1, $J = 3/2$, $F = 3/2$–5/2	226.3325	2.6	1



STOKES PARAMETERS

Can be shown that Stokes parameters can be created from combining auto- and cross-correlation products of electric fields or voltages (see Kliger 1990 for derivation):

Total Intensity $$I = E_X\overline{E_X} + E_Y\overline{E_Y}$$

Linear Polarization
$$\begin{cases} Q = E_X\overline{E_X} - E_Y\overline{E_Y} \\ U = E_X\overline{E_Y} + \overline{E_X}E_Y \end{cases}$$

Radio telescopes can get them all simultaneously!

Circular Polarization $$iV = E_X\overline{E_Y} - \overline{E_X}E_Y,$$

where the bars indicate complex conjugate and it is understood that the products are averaged over time. These time-average products can be obtained by suitable equipment that multiplies the voltages. In practice, the products are performed digitally,

The Mueller Matrix

Transfer function that expresses interchanges of power between Stokes parameters.

Correlator Output Incoming Radiation

$$\mathbf{S}_{\text{obs}} = \begin{bmatrix} I_{\text{obs}} \\ Q_{\text{obs}} \\ U_{\text{obs}} \\ V_{\text{obs}} \end{bmatrix} = M \cdot \begin{bmatrix} I_{\text{true}} \\ Q_{\text{true}} \\ U_{\text{true}} \\ V_{\text{true}} \end{bmatrix}$$

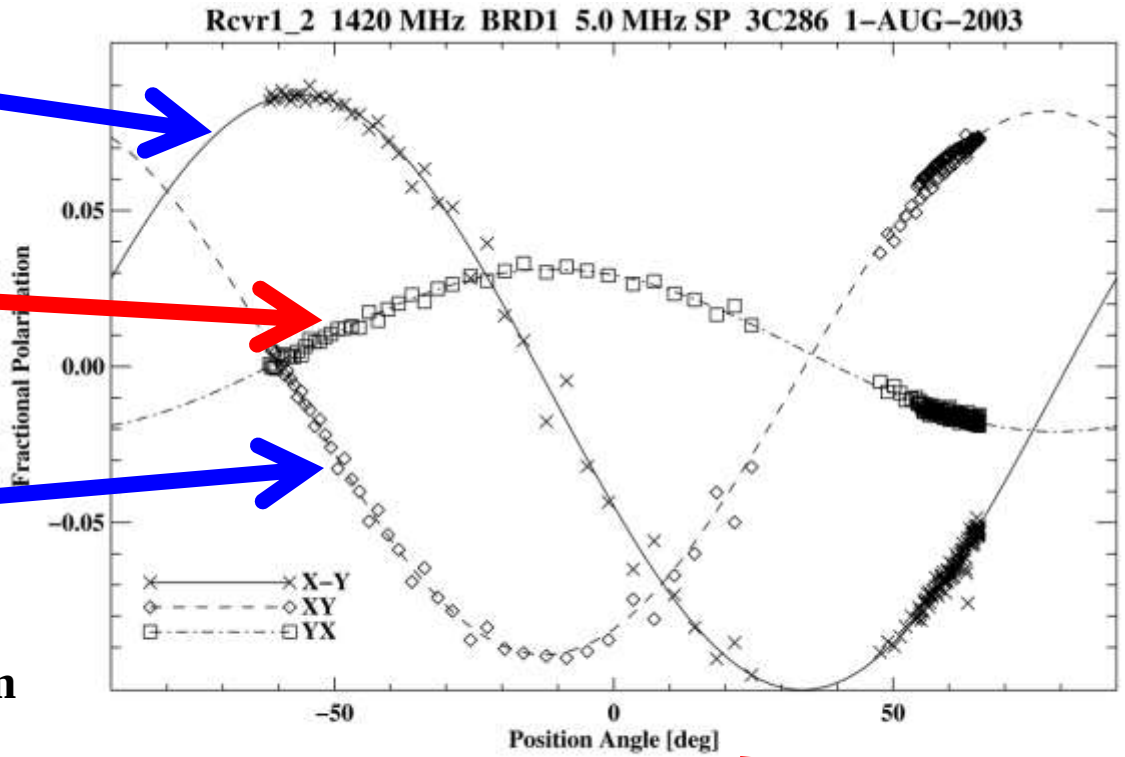
Zeeman Splitting

$$\mathbf{M} = \begin{bmatrix} m_{II} & m_{IQ} & m_{IU} & m_{IV} \\ m_{QI} & m_{QQ} & m_{QU} & m_{QV} \\ m_{UI} & m_{UQ} & m_{UU} & m_{UV} \\ m_{VI} & m_{VQ} & m_{VU} & m_{VV} \end{bmatrix}$$

Stokes Q

Stokes V

Stokes U



But linearly polarized continuum sources like 3C 286 have negligible circular polarization!

Parallactic Angle

DELTAG = −0.017 ± 0.006
PSI = −16.7 ± 1.8
ALPHA = +0.4 ± 0.9
EPSILON = +0.004 ± 0.001
PHI = +152.3 ± 23.0
Q_{SRC} = −0.037 ± 0.002
U_{SRC} = −0.085 ± 0.002
POL_{SRC} = +0.093 ± 0.002
PA_{SRC} (**UNCORRECTED FOR M_{ASTRO}**) = −56.81 ± 0.64
NR GOOD POINTS: X−Y = 149 XY = 158 YX = 160 / 160

Mueller Matrix:

	I	*Q*	*U*	*V*
I	1.0000	−0.0083	−0.0065	0.0033
Q	−0.0083	0.9999	0.0001	0.0145
U	−0.0053	−0.0042	0.9581	0.2865
V	0.0052	−0.0139	−0.2865	0.9580

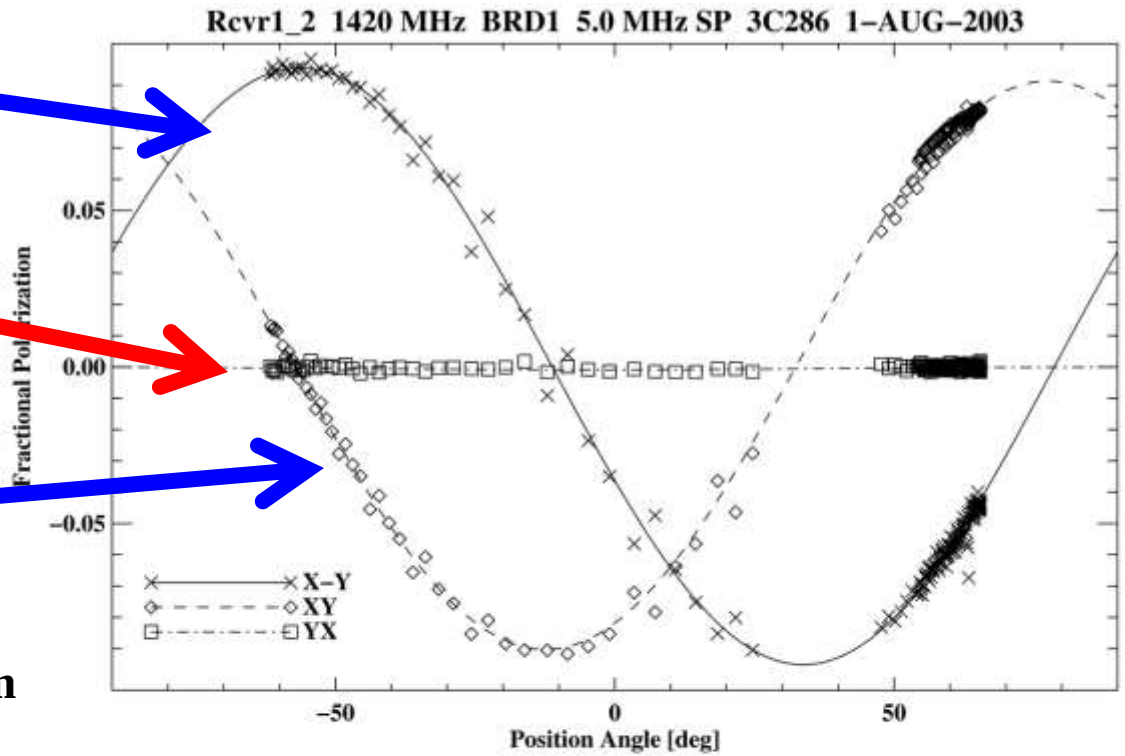
30% U into V

We must correct observations for polarization leakage!

Stokes Q

Stokes V

Stokes U



But linearly polarized continuum sources like 3C 286 have negligible circular polarization!

Parallactic Angle

DELTAG = 0.000 ± 0.006
PSI = +0.3 ± 1.8
ALPHA = −0.0 ± 0.9
EPSILON = +0.000 ± 0.001
PHI = −39.8 ± 235.4
Q_{SRC} = −0.037 ± 0.002
U_{SRC} = −0.085 ± 0.002
POL_{SRC} = +0.093 ± 0.002
PA_{SRC} (**UNCORRECTED FOR M_{ASTRO}**) = −56.82 ± 0.64
NR GOOD POINTS: X-Y = 149 XY = 158 YX = 158 / 160

Mueller Matrix:

	I	*Q*	*U*	*V*
I	1.0000	0.0002	0.0006	−0.0005
Q	0.0002	1.0000	0.0000	−0.0012
U	0.0006	−0.0000	1.0000	−0.0044
V	−0.0005	0.0012	0.0044	1.0000

< 1% U into V

We must correct observations for polarization leakage!

"The measurements have been corrected for everything you correct such measurements for."

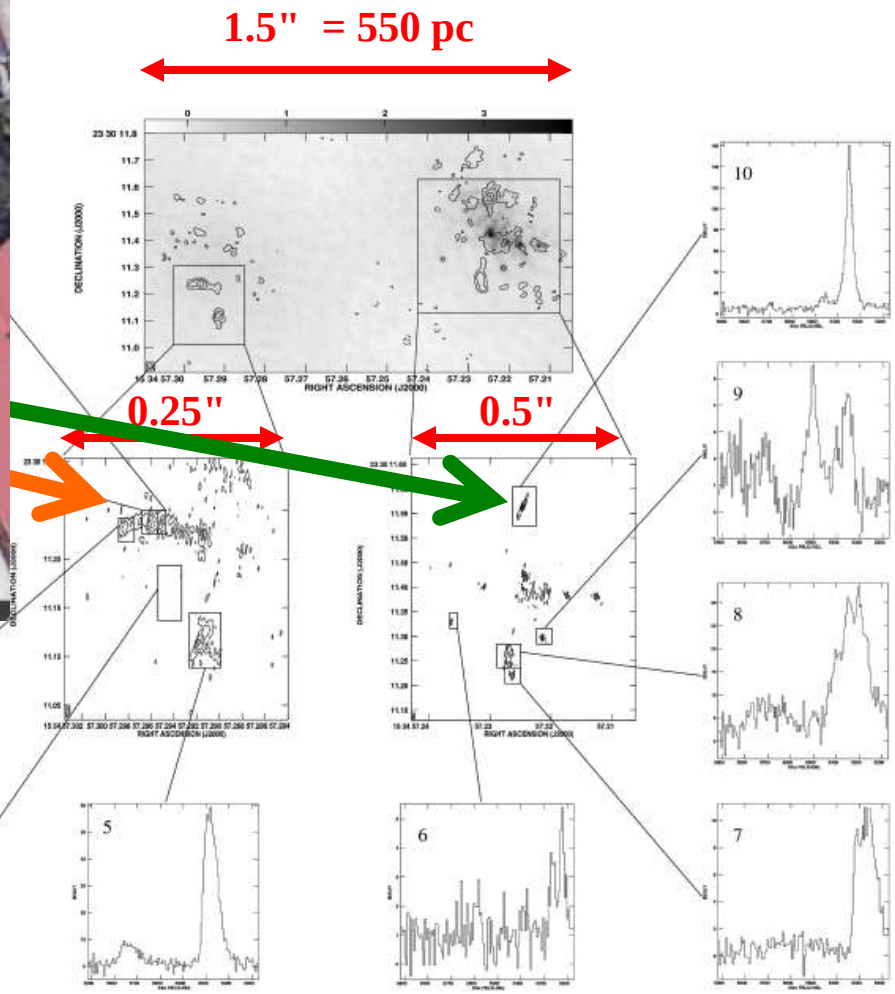
-- GART WESTERHOUT, 1966



1927-2012

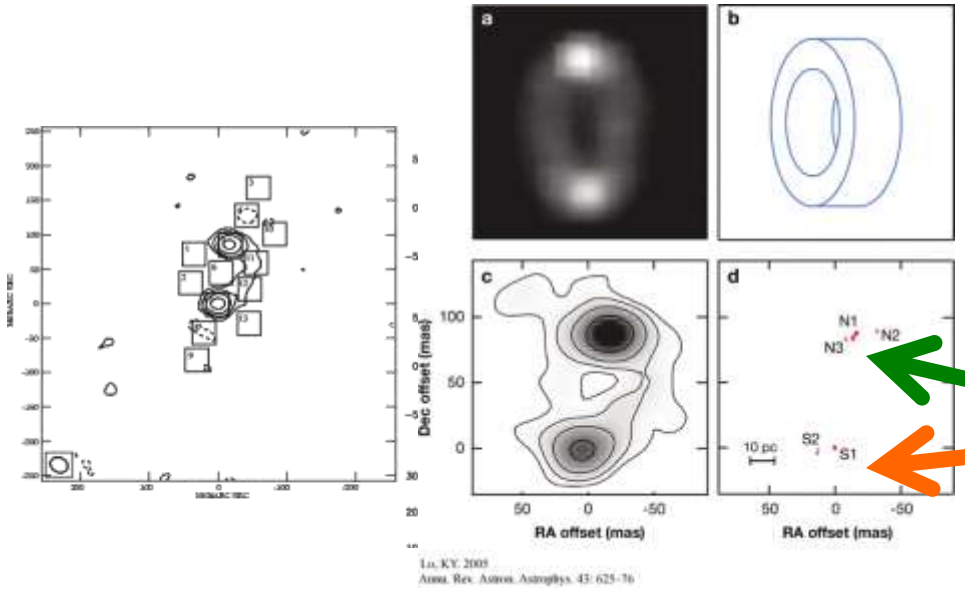
***Credit*: Stephen Ng**

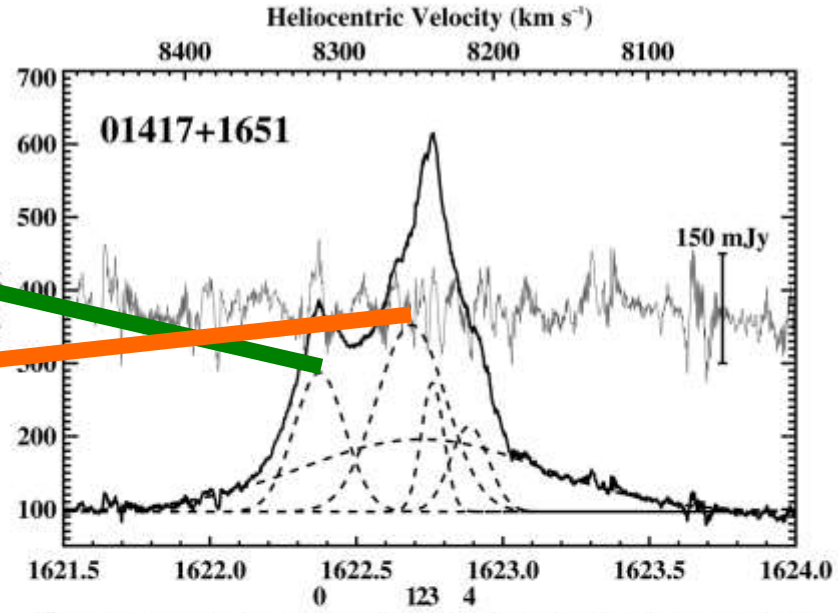


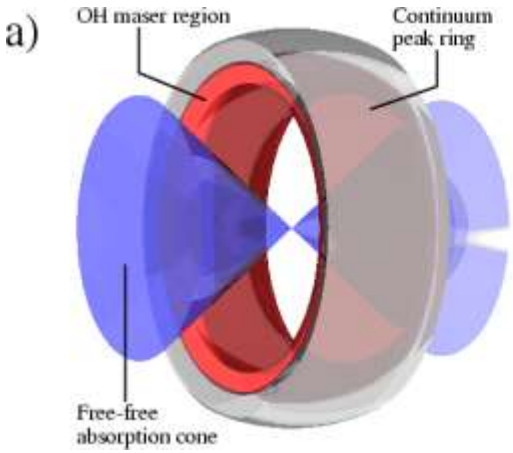


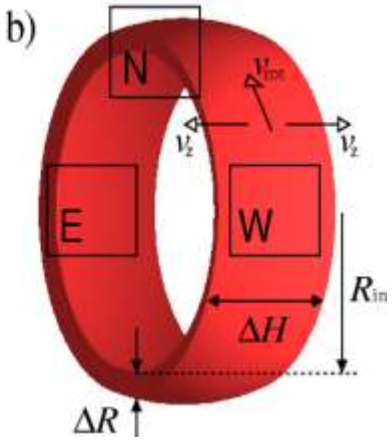
Rovilos, Diamond, Lonsdale[2], & Smith 2003

III Zw 35





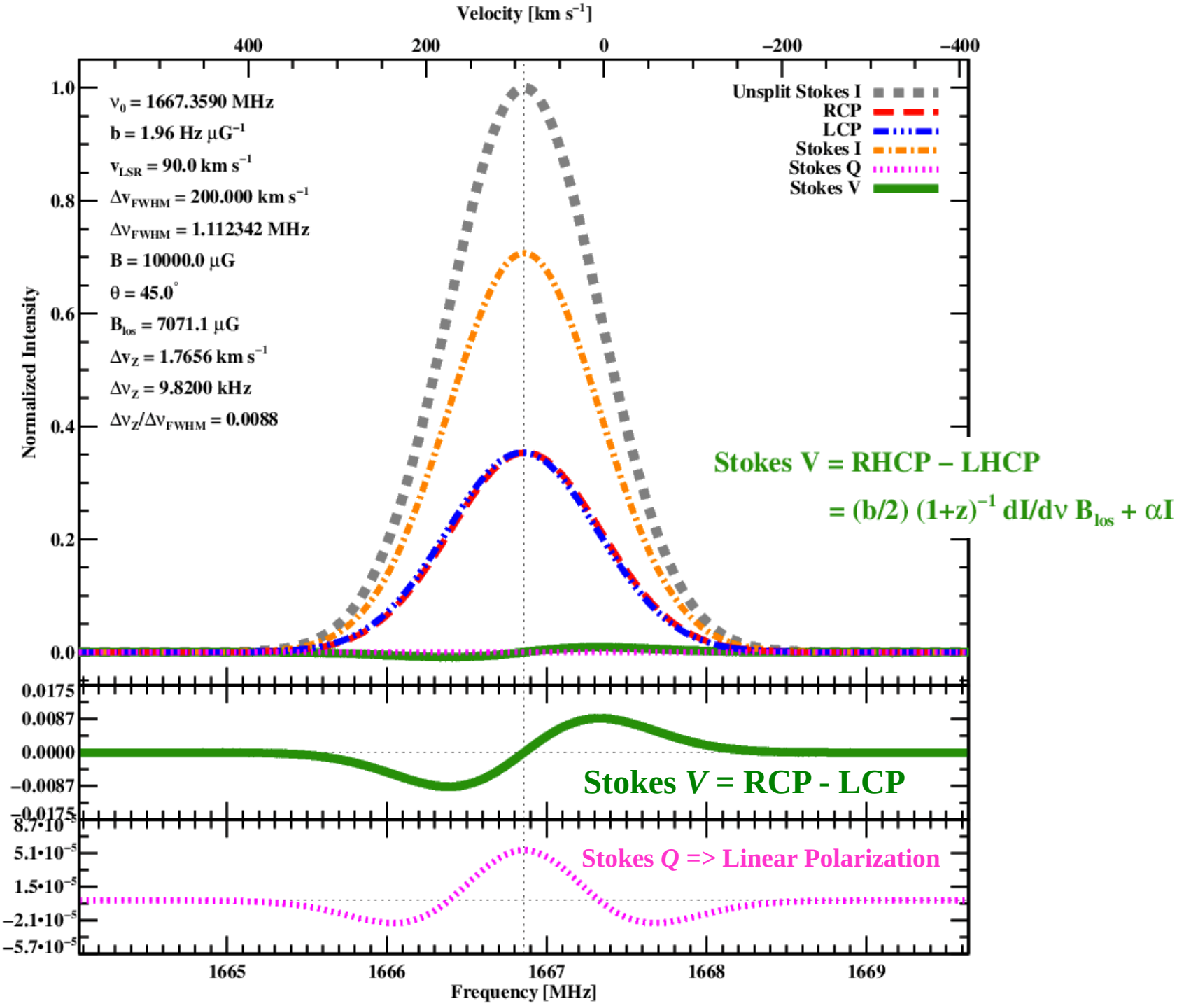




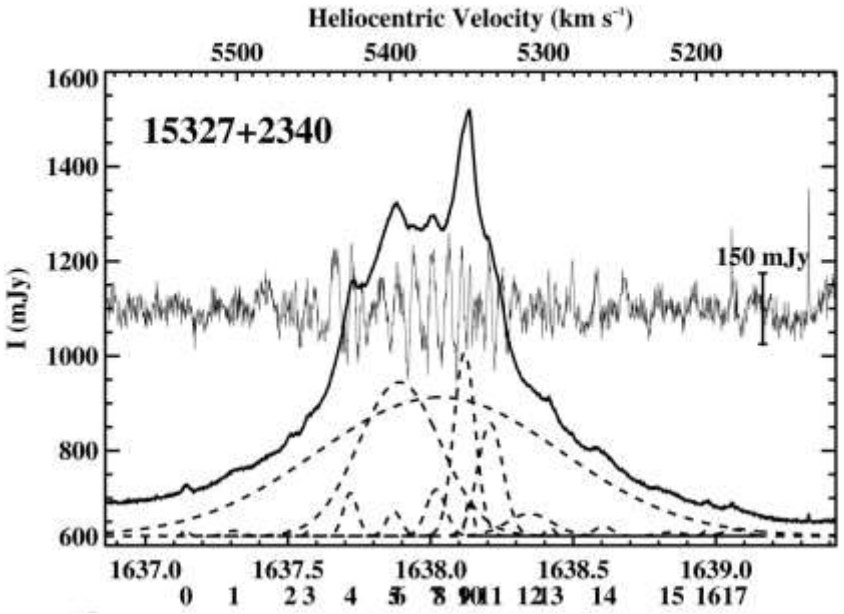


Pihlström, Conway, Booth, Diamond, & Polatidis 2001

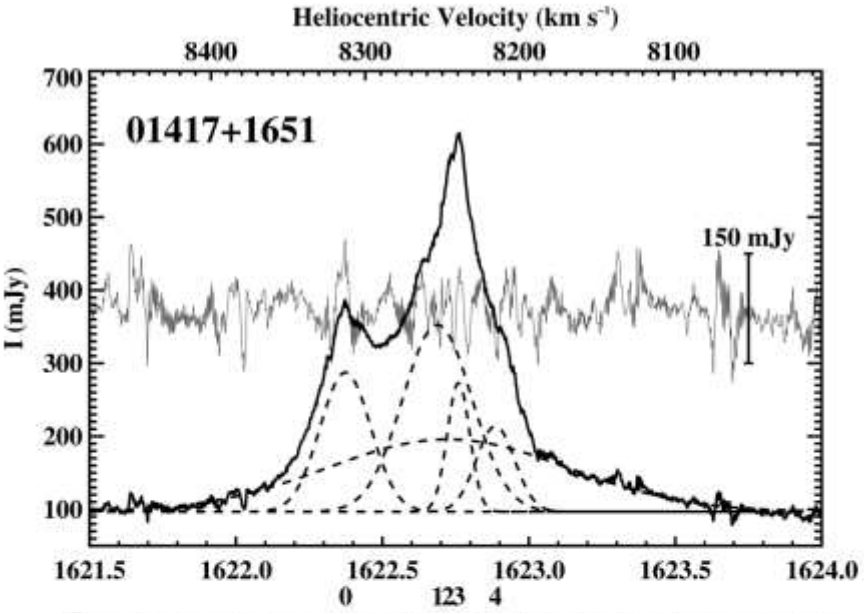
Parra, Conway, Elitzur, & Pihlström 2005


Velocity [km s^{-1}]
400
200
0
−200
−400
ν_0 = 1667.3590 MHz
b = 1.96 Hz μG^{-1}
v_{LSR} = 90.0 km s^{-1}
Δv_{FWHM} = 200.000 km s^{-1}
$\Delta\nu_{FWHM}$ = 1.112342 MHz
B = 10000.0 μG
θ = 45.0°
B_{los} = 7071.1 μG
Δv_Z = 1.7656 km s^{-1}
$\Delta\nu_Z$ = 9.8200 kHz
$\Delta\nu_Z/\Delta\nu_{FWHM}$ = 0.0088
Unsplit Stokes I
RCP
LCP
Stokes I
Stokes Q
Stokes V
Normalized Intensity
1.0
0.8
0.6
0.4
0.2
0.0
Stokes V = RHCP – LHCP
= (b/2) (1+z)$^{-1}$ dI/dν B_{los} + αI
0.0175
0.0087
0.0000
−0.0087
−0.0175
Stokes V = RCP - LCP
8.7•10^{-5}
5.1•10^{-5}
1.5•10^{-5}
−2.1•10^{-5}
−5.7•10^{-5}
Stokes Q => Linear Polarization
1665
1666
1667
1668
1669
Frequency [MHz]

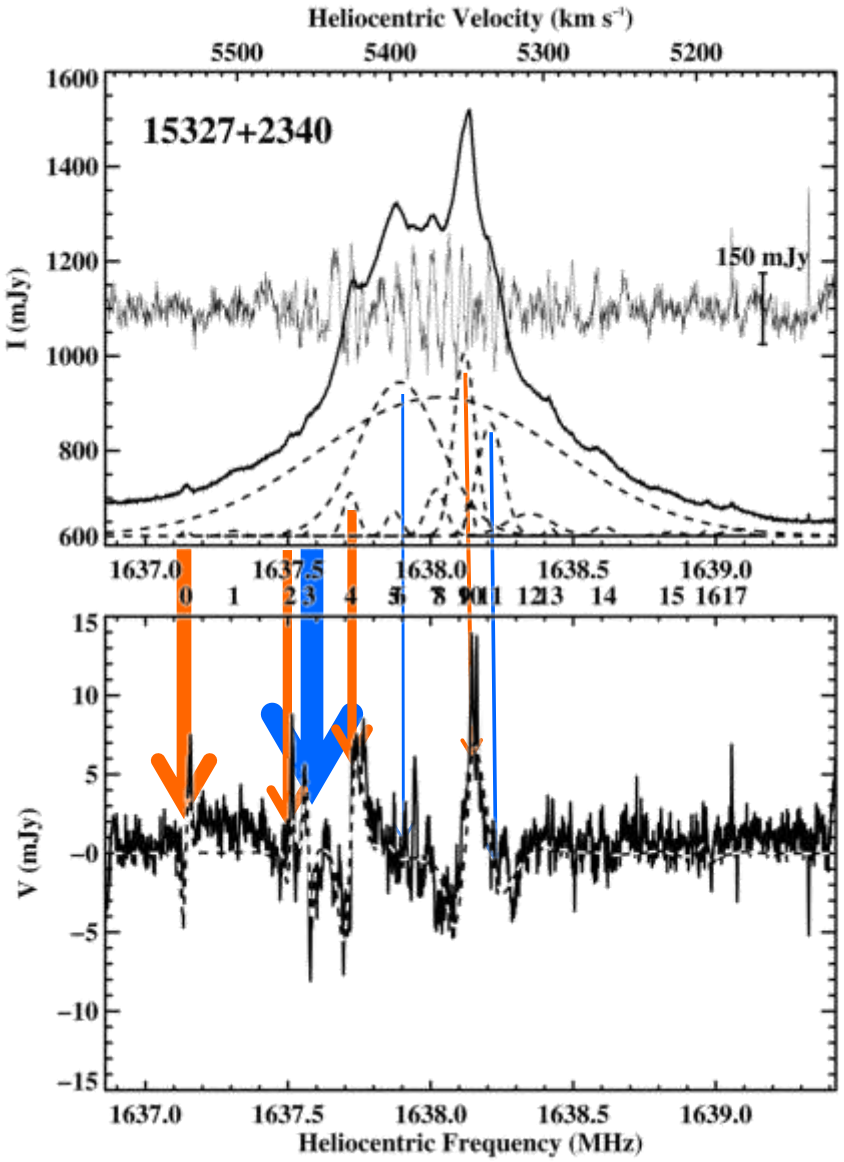
Arp 220



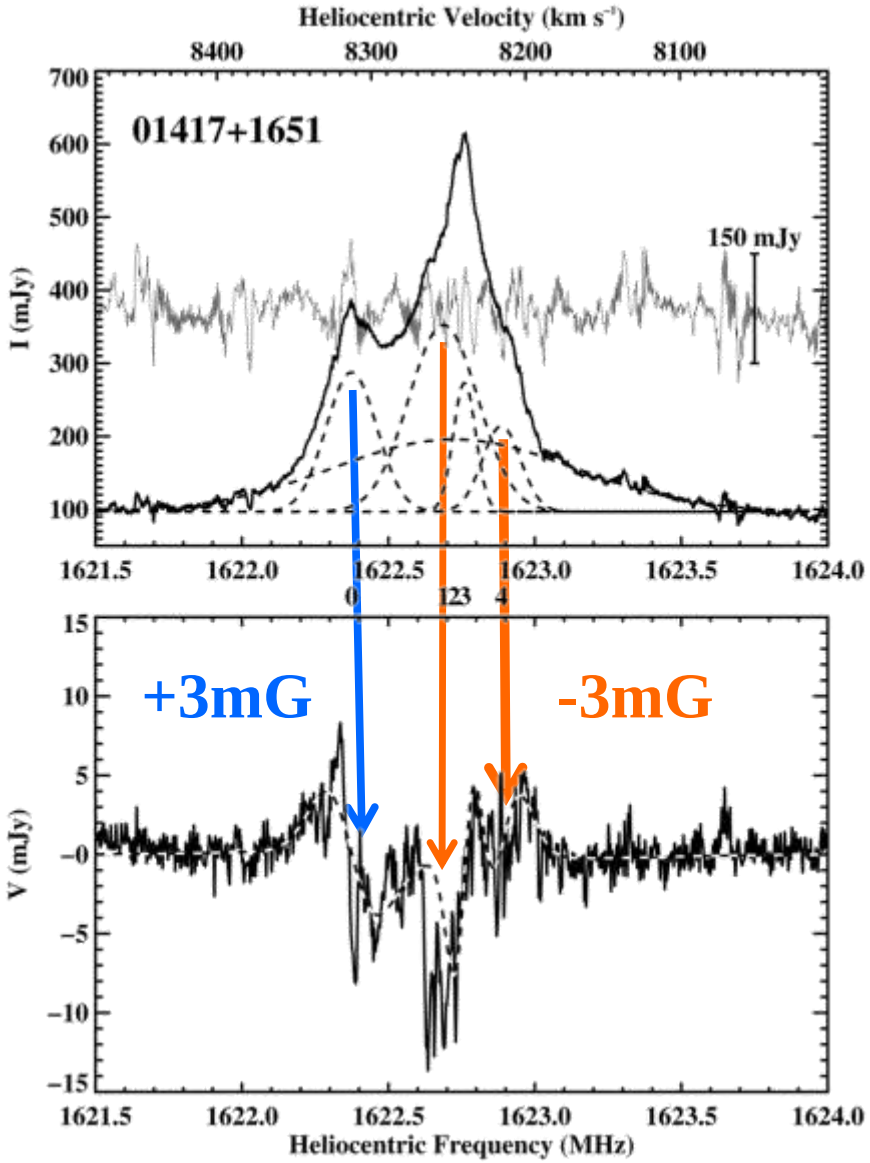
III Zw 35



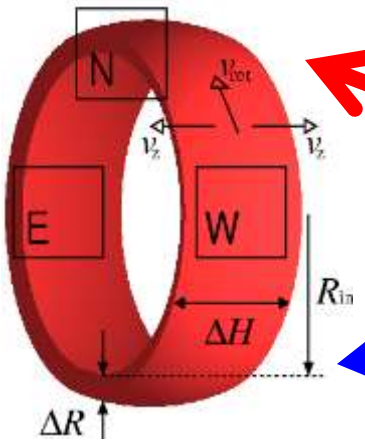
Arp 220

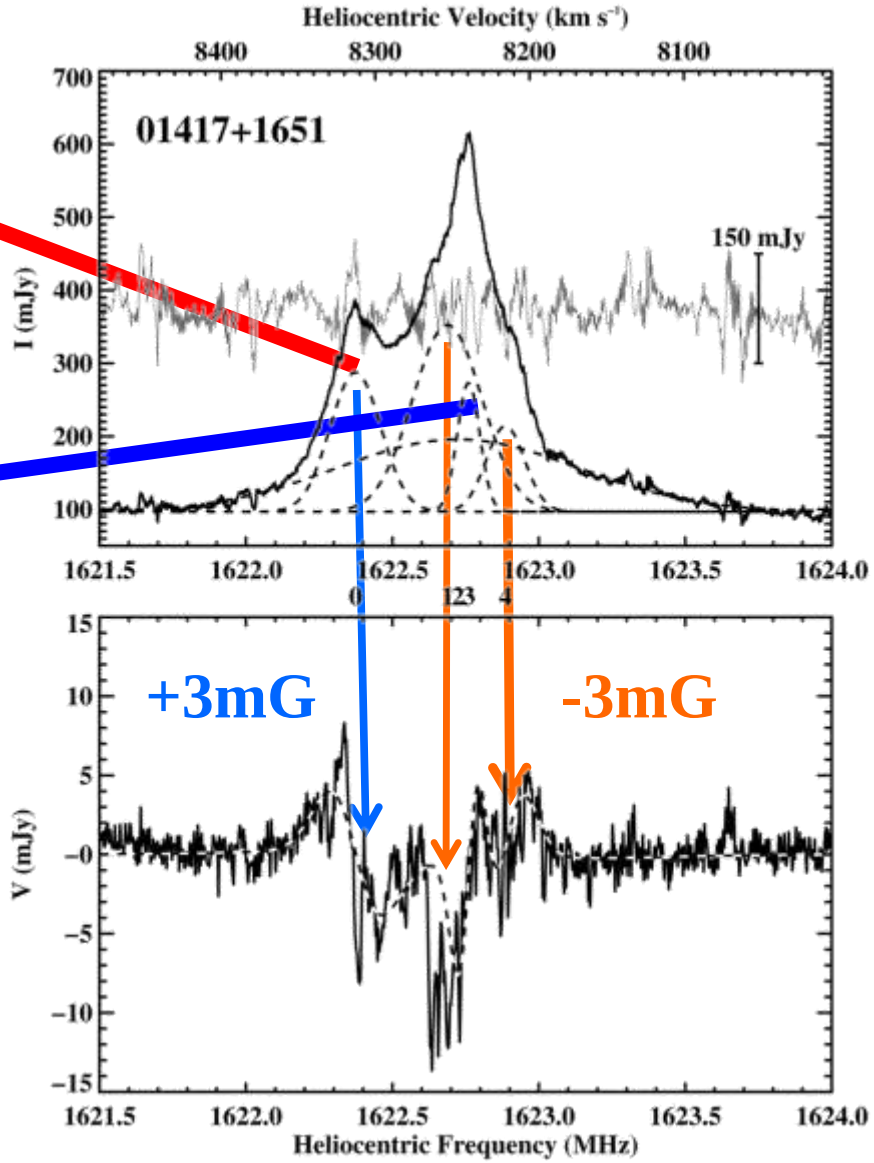


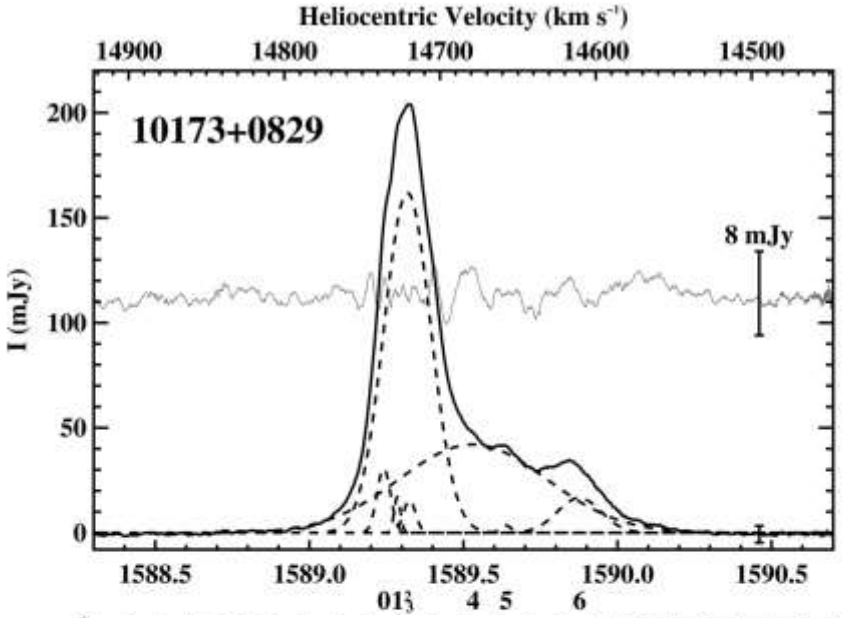
III Zw 35

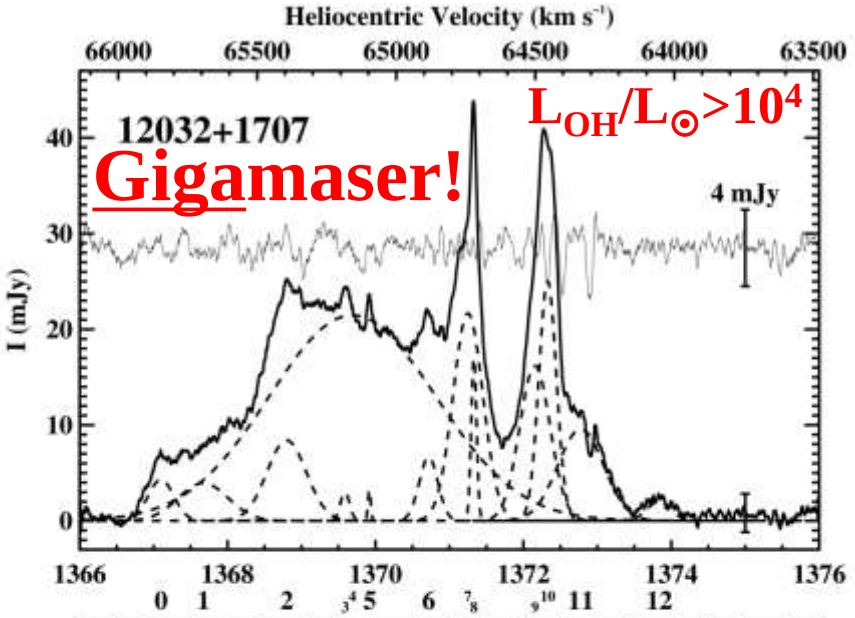


III Zw 35

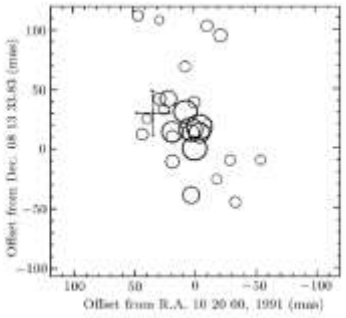

N
E
W
v_{tor}
v_z
v_z
R_{in}
ΔH
ΔR

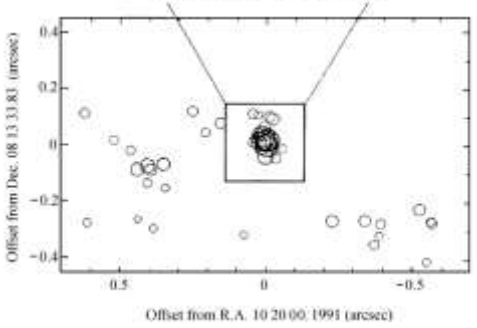

Heliocentric Velocity (km s⁻¹)
8400
8300
8200
8100
01417+1651
150 mJy
I (mJy)
700
600
500
400
300
200
100
1621.5
1622.0
1622.5
1623.0
1623.5
1624.0
0
123
4
+3mG
-3mG
V (mJy)
15
10
5
−0
−5
−10
−15
Heliocentric Frequency (MHz)





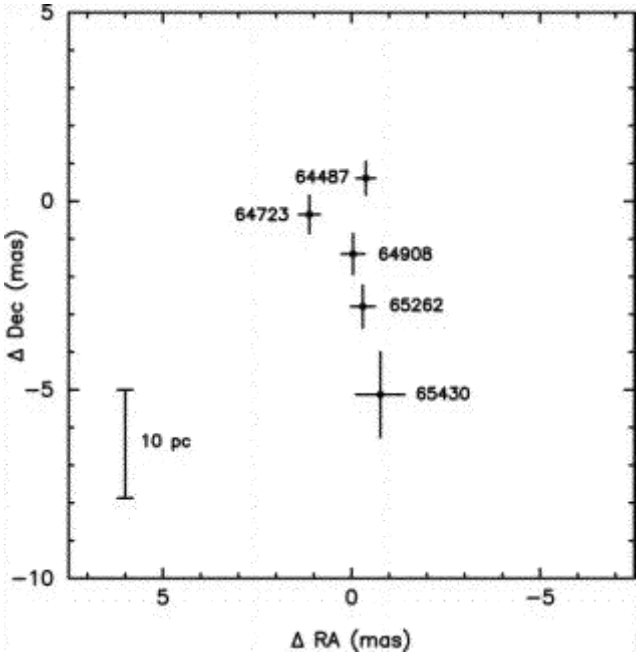
200 pc

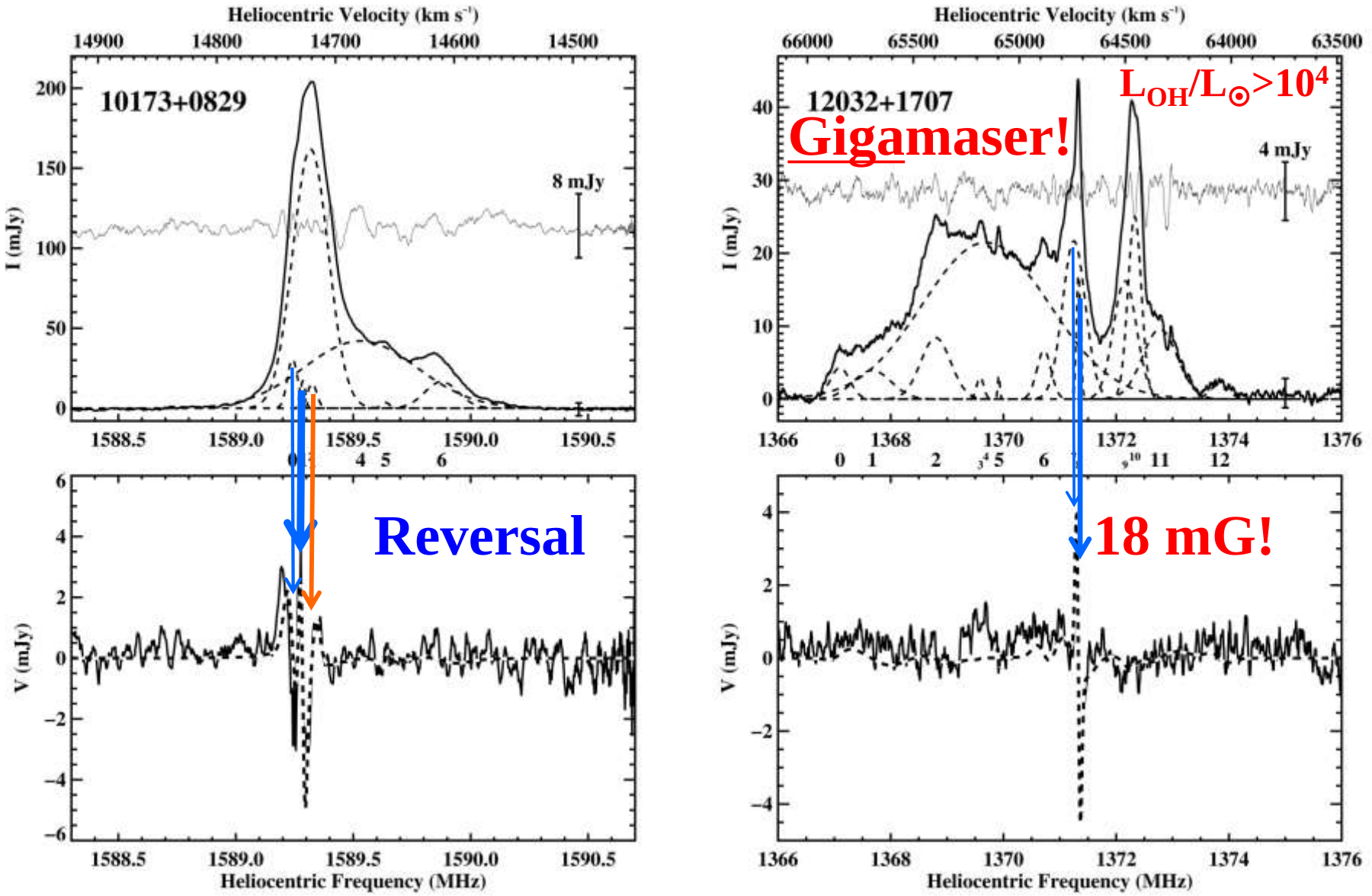




Yu 2005

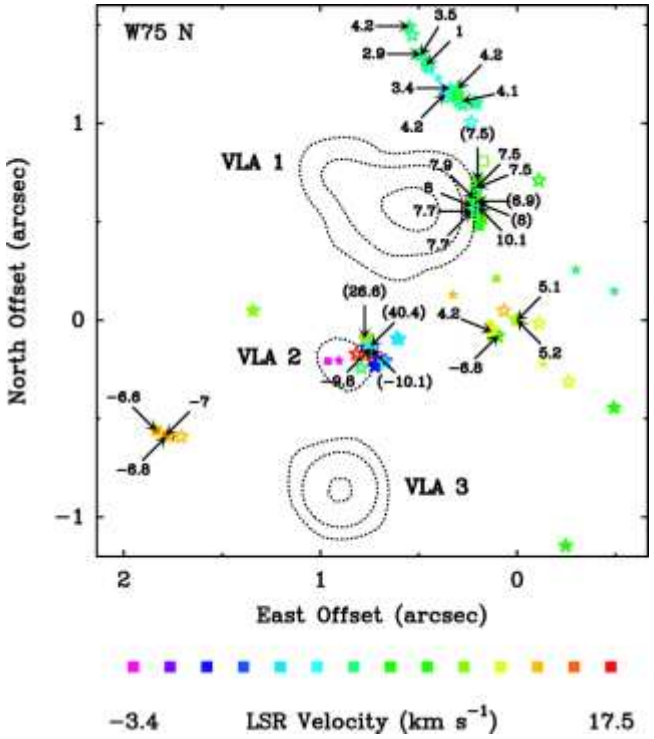
Pihlström, Baan, Darling, & Klöckner 2005





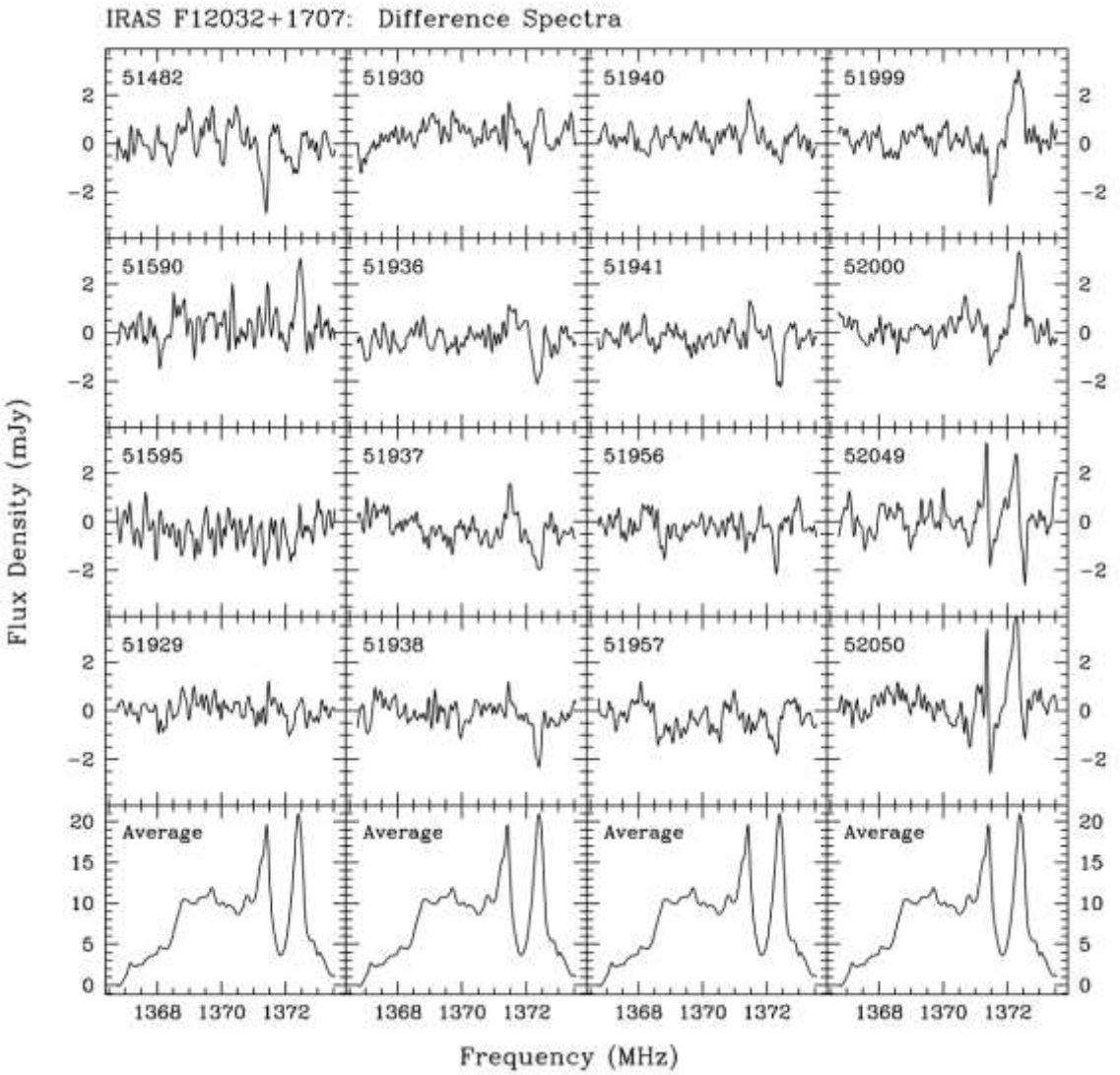
14 B fields in 5 of 8 ULIRGs searched.

Time-Variable Masers :: Big Fields?



W75N
Slysh & Migenes
Fish & Reid

Jeremy Darling





THE ASTROPHYSICAL JOURNAL, 763:8 (24pp), 2013 January 20
© 2013. The American Astronomical Society. All rights reserved. Printed in the U.S.A.
doi:10.1088/0004-637X/763/1/8

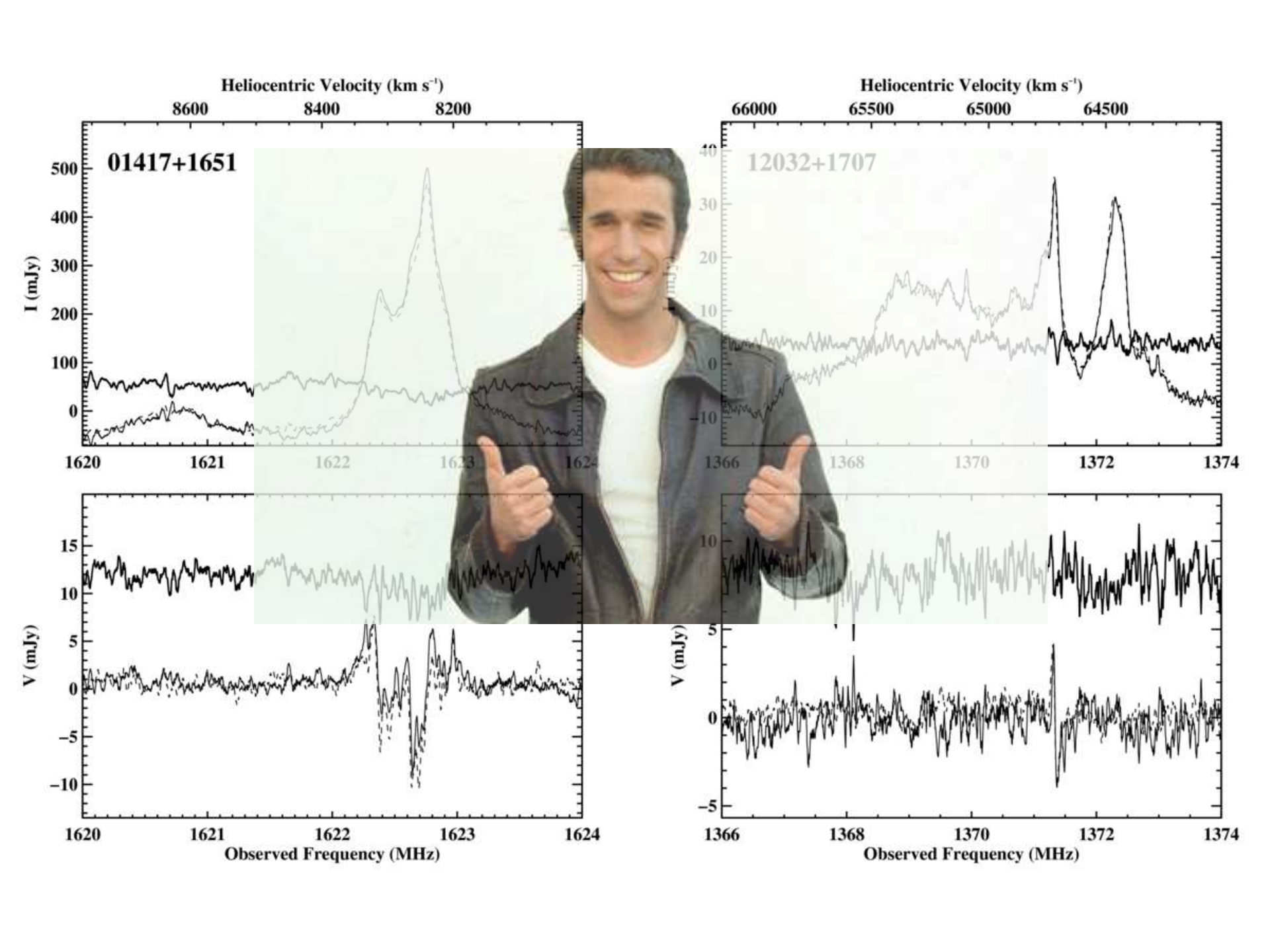
AN ARECIBO SURVEY FOR ZEEMAN SPLITTING IN OH MEGAMASER GALAXIES

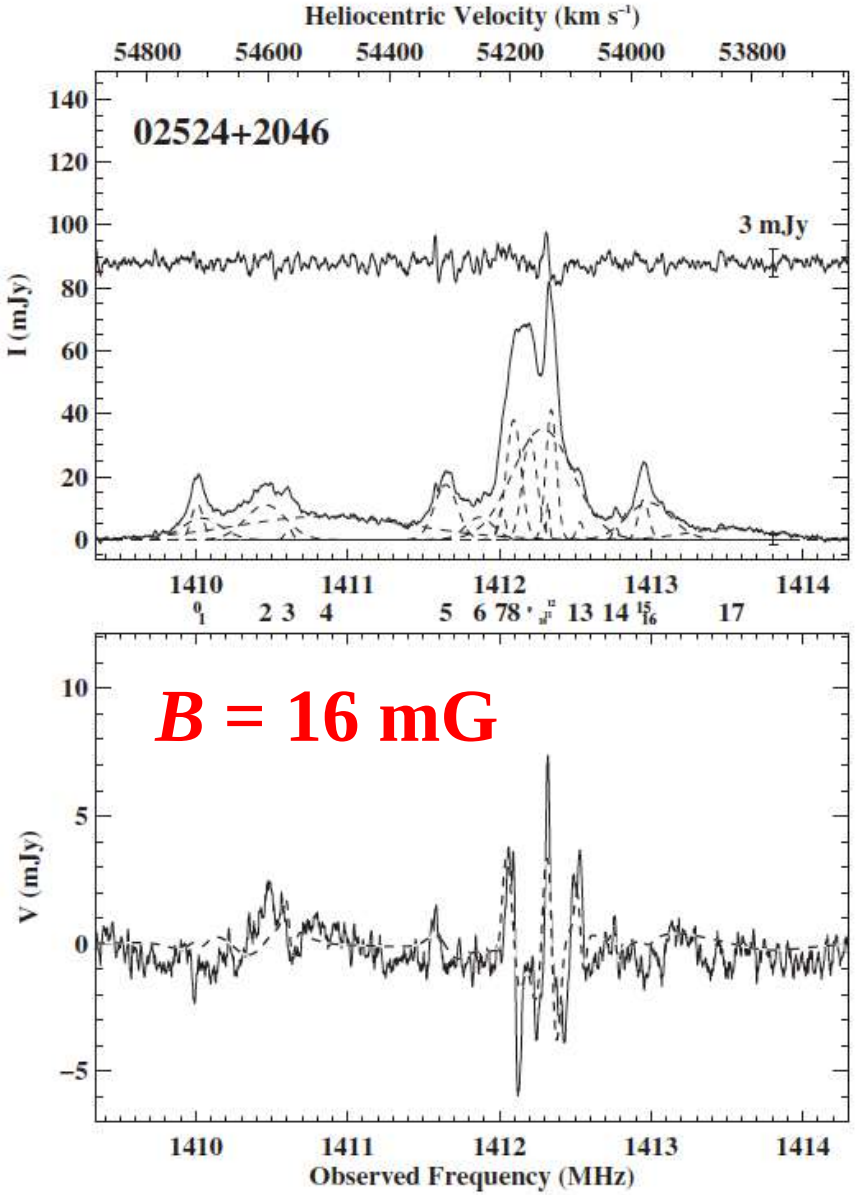
JAMES MCBRIDE AND CARL HEILES
Department of Astronomy, University of California, Berkeley, CA 94720-3411, USA; jmcbride@astro.berkeley.edu, heiles@astro.berkeley.edu
Received 2012 September 28; accepted 2012 November 7; published 2012 December 27

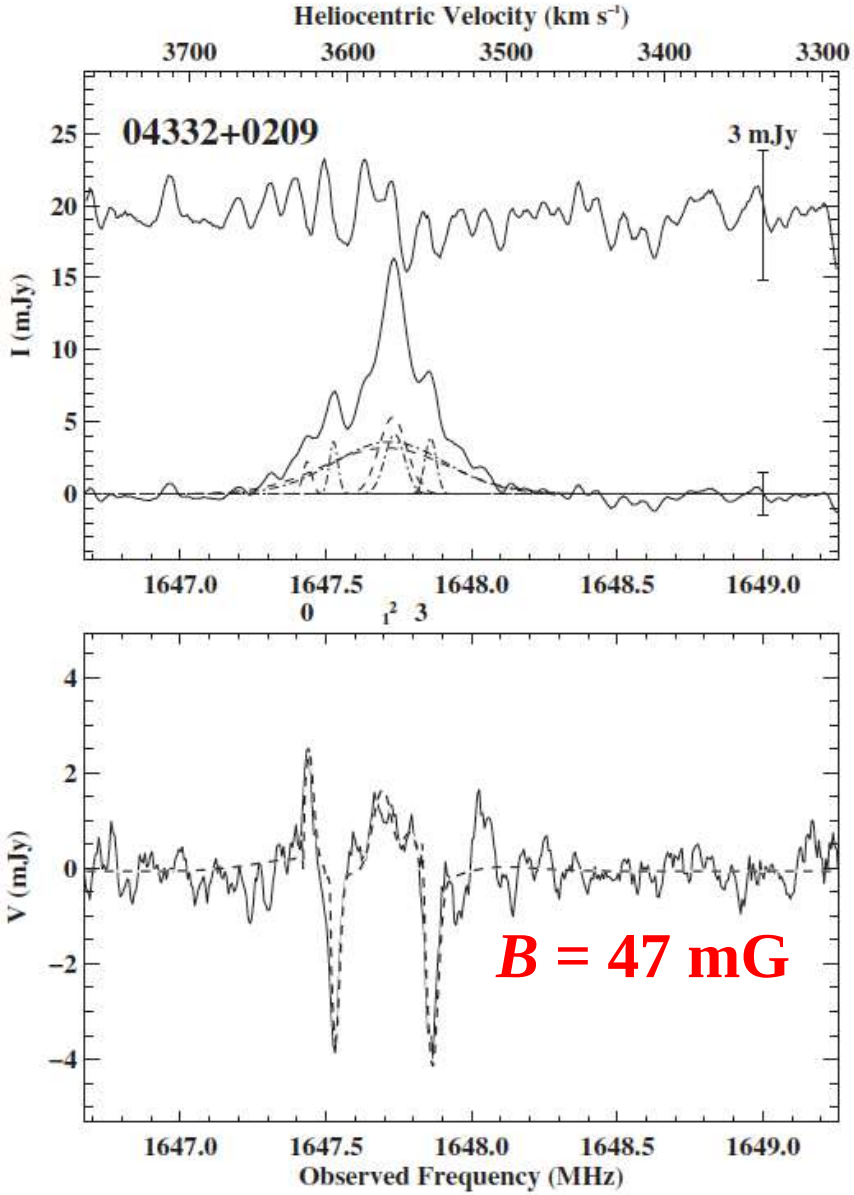
ABSTRACT

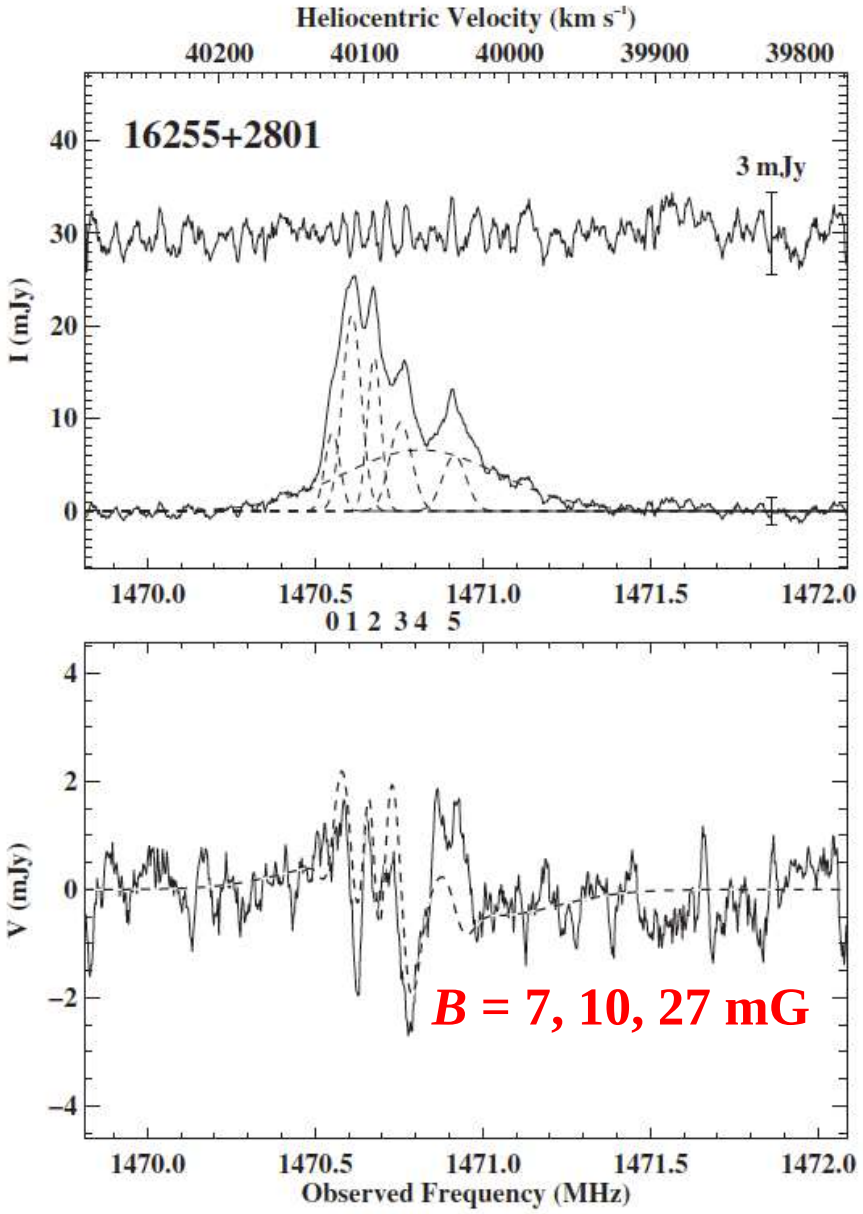
We present the results of a comprehensive survey using the Arecibo Observatory for Zeeman splitting of OH lines in OH megamasers (OHMs). A total of 77 sources were observed with the Arecibo telescope. Of these, maser emission could not be detected for eight sources, and two sources were only ambiguously detected. Another 27 sources were detected at low signal-to-noise ratios or with interference that prevented placing any useful limits on the presence of magnetic fields. In 26 sources, it was possible to place upper limits on the magnitude of magnetic fields, typically between 10 and 30 mG. For 14 sources, the Stokes *V* spectra exhibit features consistent with Zeeman splitting. Eleven of these 14 are new detections, and the remaining three are re-detections of Stokes *V* detections in Robishaw et al. Among confident new detections, we derive magnetic fields associated with maser regions with magnitudes ranging from 6.1 to 27.6 mG. The distribution of magnetic field strengths suggests the magnetic fields in OH masing clouds in OHMs are larger than those in Galactic OH masers. The results are consistent with magnetic fields playing a dynamically important role in OH masing clouds in OHMs.

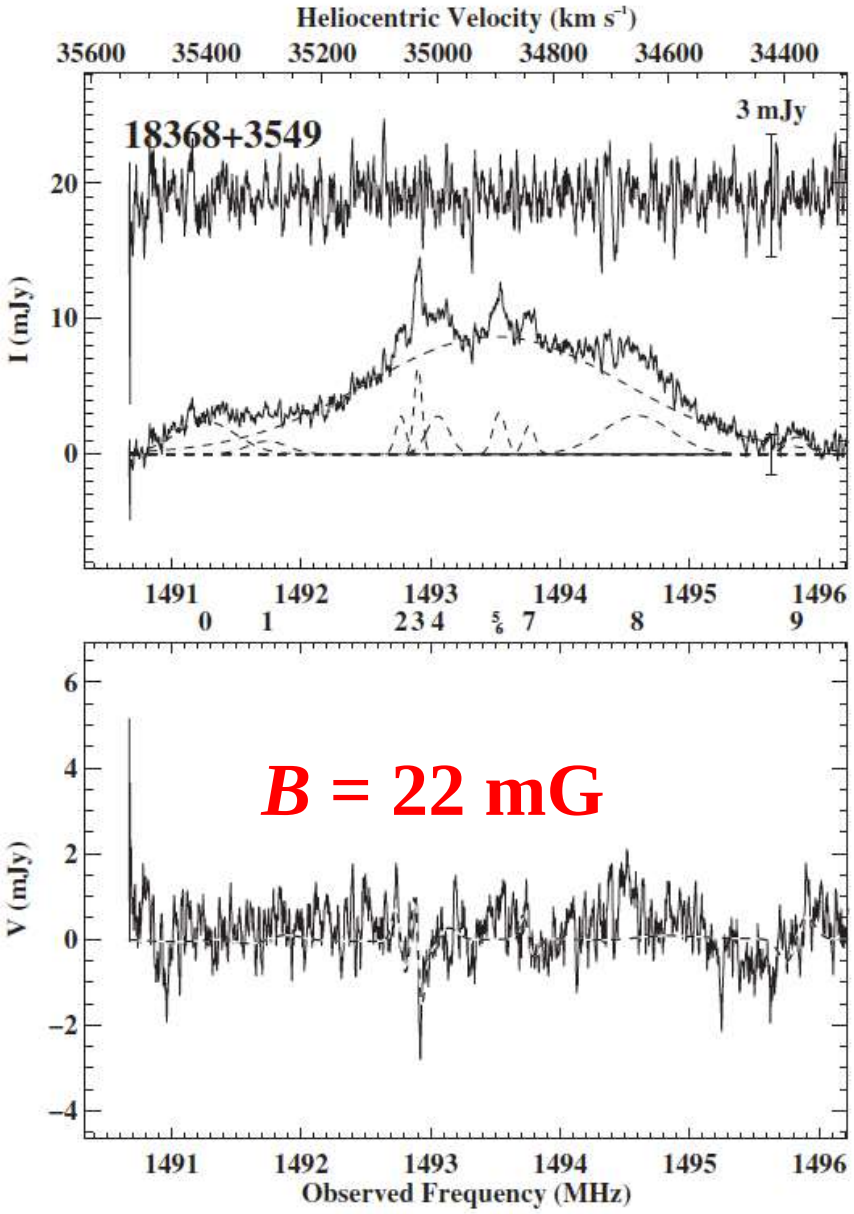
- All of the 77 OHMs observable at Arecibo.
  - 450 hours
  - Re-observed 6 OHMs from Robishaw et al. (2008)

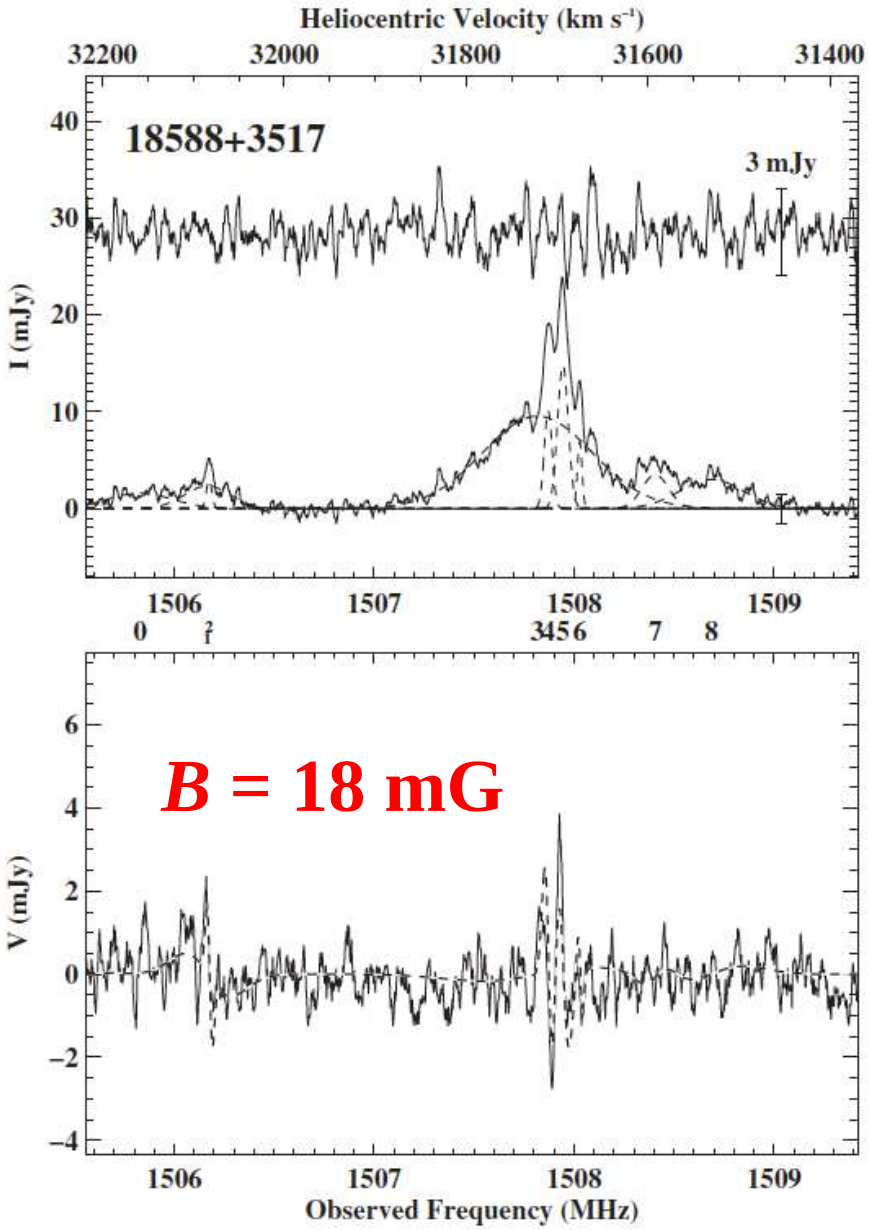

Heliocentric Velocity (km s^{-1})
8600
8400
8200
01417+1651
I (mJy)
500
400
300
200
100
0
1620
1621
1622
1623
1624
V (mJy)
15
10
5
0
−5
−10
Observed Frequency (MHz)
Heliocentric Velocity (km s^{-1})
66000
65500
65000
64500
12032+1707
40
30
20
10
0
−10
1366
1368
1370
1372
1374
V (mJy)
10
5
0
−5
Observed Frequency (MHz)

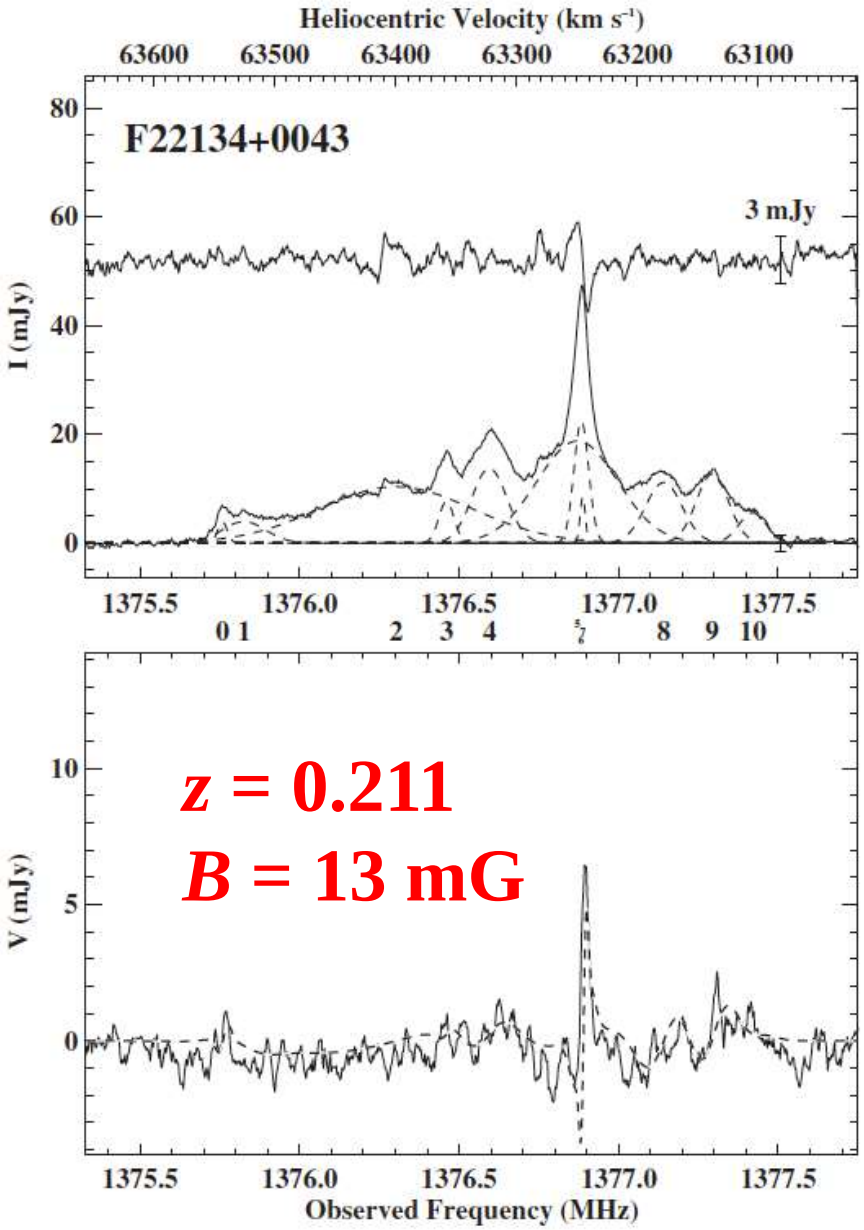

Heliocentric Velocity (km s⁻¹)
54800
54600
54400
54200
54000
53800
02524+2046
3 mJy
I (mJy)
140
120
100
80
60
40
20
0
1410
1411
1412
1413
1414
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
B = 16 mG
V (mJy)
10
5
0
−5
1410
1411
1412
1413
1414
Observed Frequency (MHz)


Heliocentric Velocity (km s⁻¹)
3700
3600
3500
3400
3300
04332+0209
3 mJy
I (mJy)
25
20
15
10
5
0
1647.0
1647.5
1648.0
1648.5
1649.0
0 1 2 3
V (mJy)
4
2
0
−2
−4
B = 47 mG
1647.0
1647.5
1648.0
1648.5
1649.0
Observed Frequency (MHz)

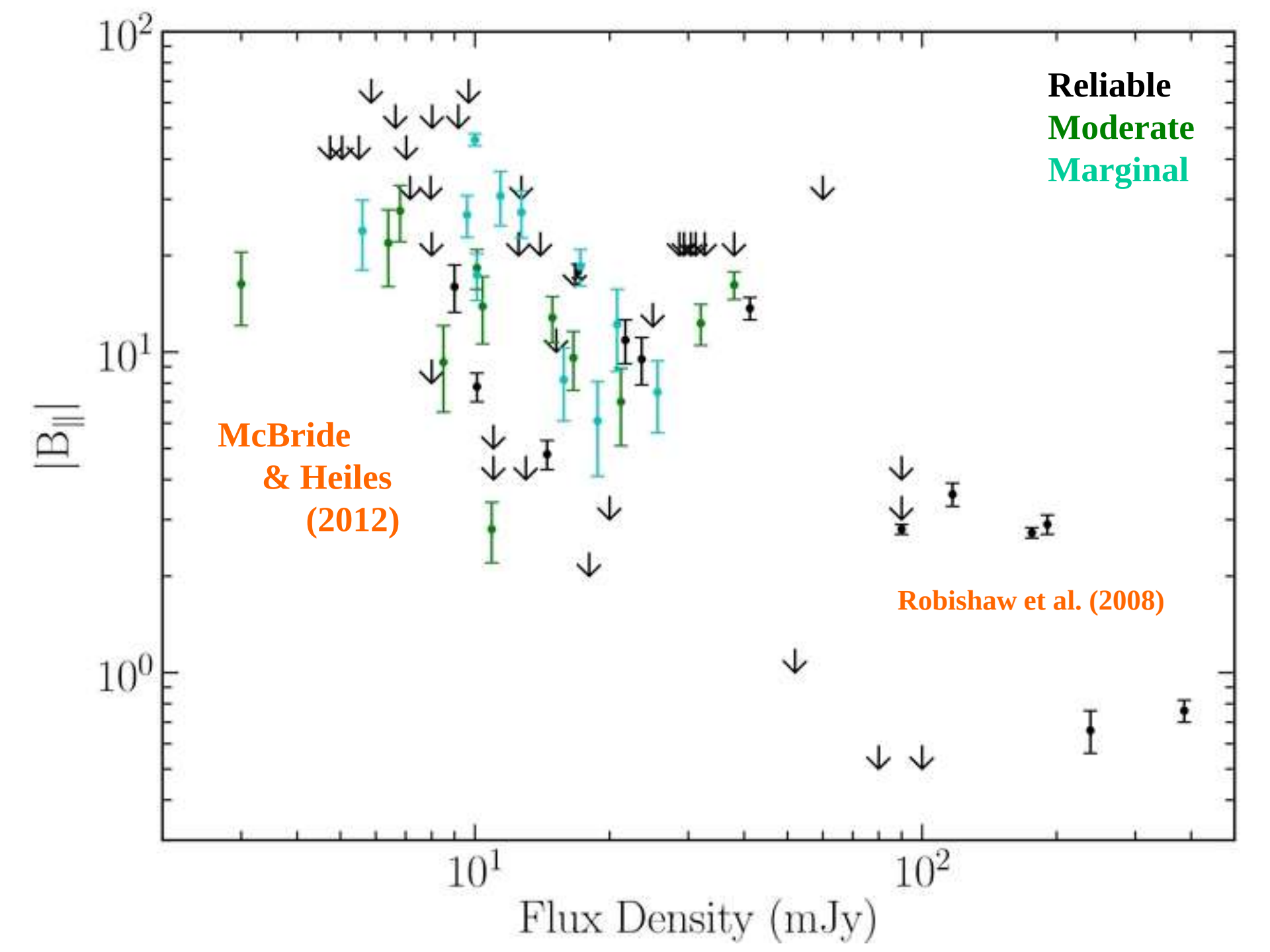

Heliocentric Velocity (km s^{-1})
40200
40100
40000
39900
39800
16255+2801
3 mJy
I (mJy)
40
30
20
10
0
1470.0
1470.5
1471.0
1471.5
1472.0
0 1 2 3 4 5
V (mJy)
4
2
0
−2
−4
B = 7, 10, 27 mG
Observed Frequency (MHz)


Heliocentric Velocity (km s^{-1})
35600
35400
35200
35000
34800
34600
34400
18368+3549
3 mJy
I (mJy)
20
10
0
1491
1492
1493
1494
1495
1496
0
1
2 3 4
5
6
7
8
9
V (mJy)
6
4
2
0
−2
−4
B = 22 mG
Observed Frequency (MHz)


Heliocentric Velocity (km s⁻¹)
32200
32000
31800
31600
31400
18588+3517
3 mJy
I (mJy)
40
30
20
10
0
1506
1507
1508
1509
0
1
3
4
5
6
7
8
V (mJy)
6
4
2
0
−2
−4
B = 18 mG
Observed Frequency (MHz)


Heliocentric Velocity (km s⁻¹)
63600
63500
63400
63300
63200
63100
F22134+0043
3 mJy
I (mJy)
80
60
40
20
0
1375.5
1376.0
1376.5
1377.0
1377.5
0
1
2
3
4
5
8
9
10
V (mJy)
10
5
0
z = 0.211
B = 13 mG
Observed Frequency (MHz)

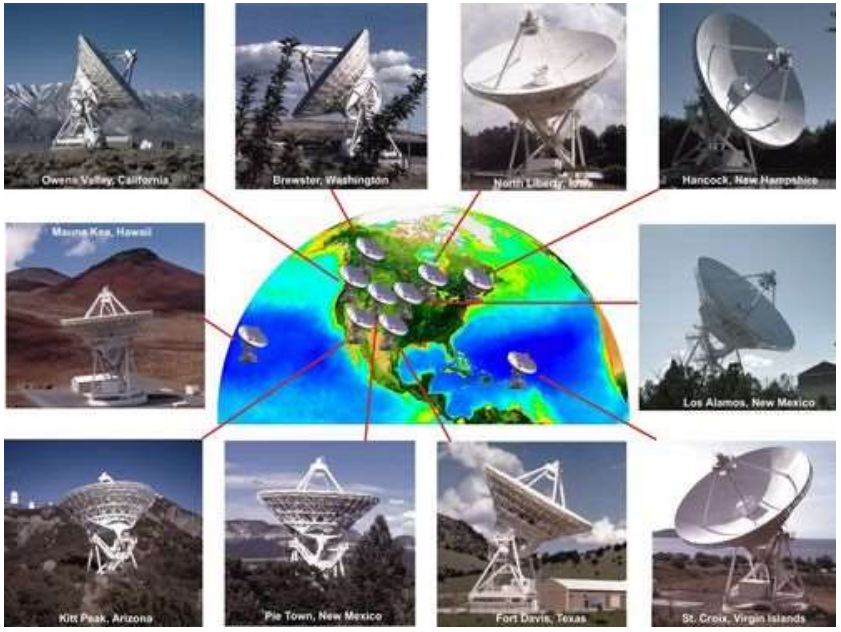
- All of the 77 OHMs observable at Arecibo.
  - 450 hours
  - Re-observed 6 OHMs from Robishaw et al. (2008)
    - Confirmed 3 previous detections.
    - Measured 1-10% variability in Stokes I.
      - No variability in Stokes V.
    - Showed 1 Robishaw detection was RFI.
  - Discovered 8 new Zeeman detections.
  - An additional 3 detections marginal.
  - 63 non-detections
  - No Zeeman detections at 1612 or 1720 MHz.
- None of the new detections have any VLBI observations!


Reliable
Moderate
Marginal
McBride & Heiles (2012)
Robishaw et al. (2008)
10^2
10^1
10^0
$|B_\parallel|$
10^1
10^2
Flux Density (mJy)



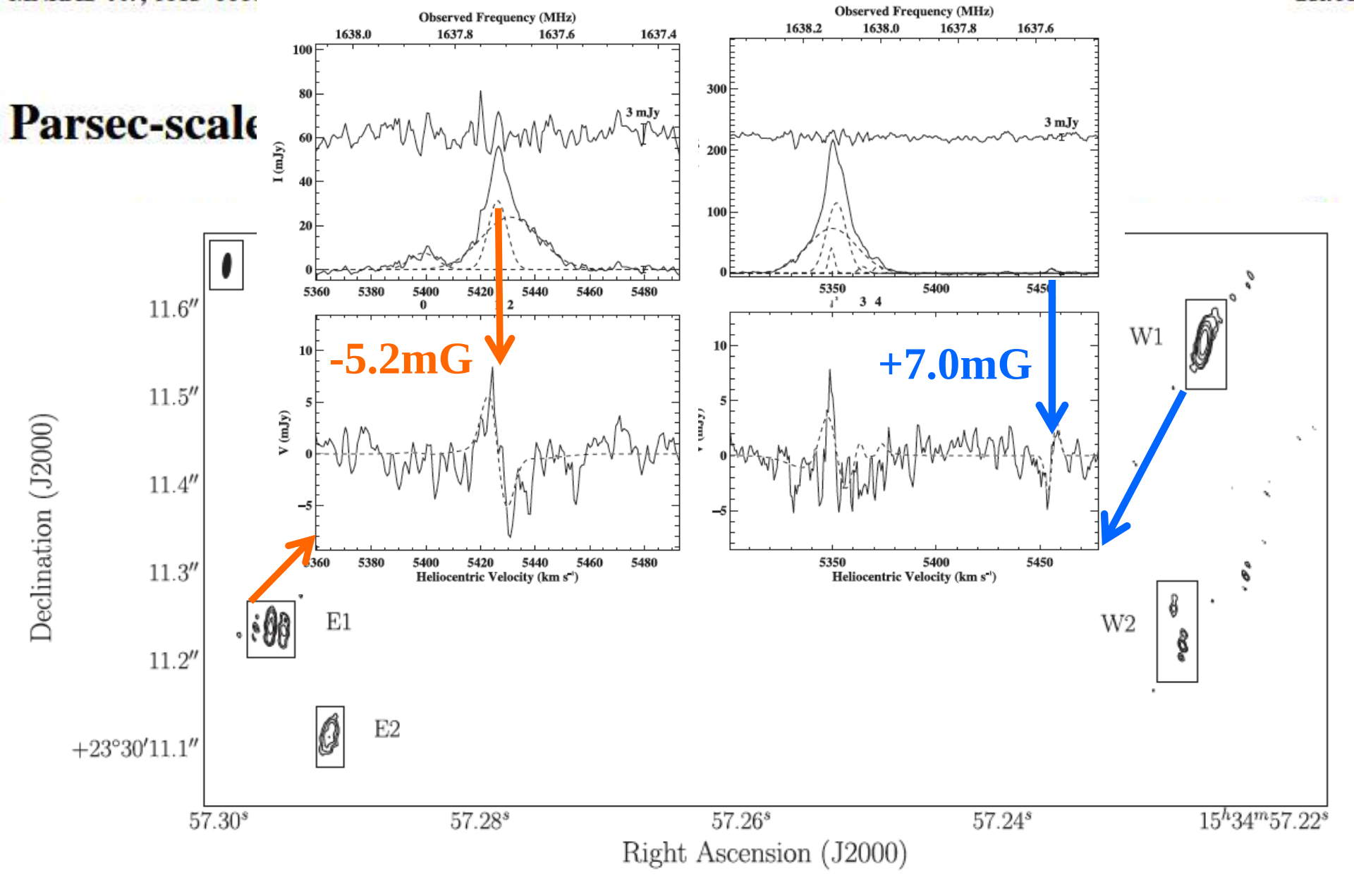



Very Large Array


Owens Valley, California
Brewster, Washington
North Liberty, Iowa
Hancock, New Hampshire
Mauna Kea, Hawaii
Los Alamos, New Mexico
Kitt Peak, Arizona
Pie Town, New Mexico
Fort Davis, Texas
St. Croix, Virgin Islands

Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY
MNRAS 447, 1103–111 (2015)
doi:10

Parsec-scale



FAST: The Five-hundred meter Aperture Spherical radio Telescope



The Square Kilometer Array



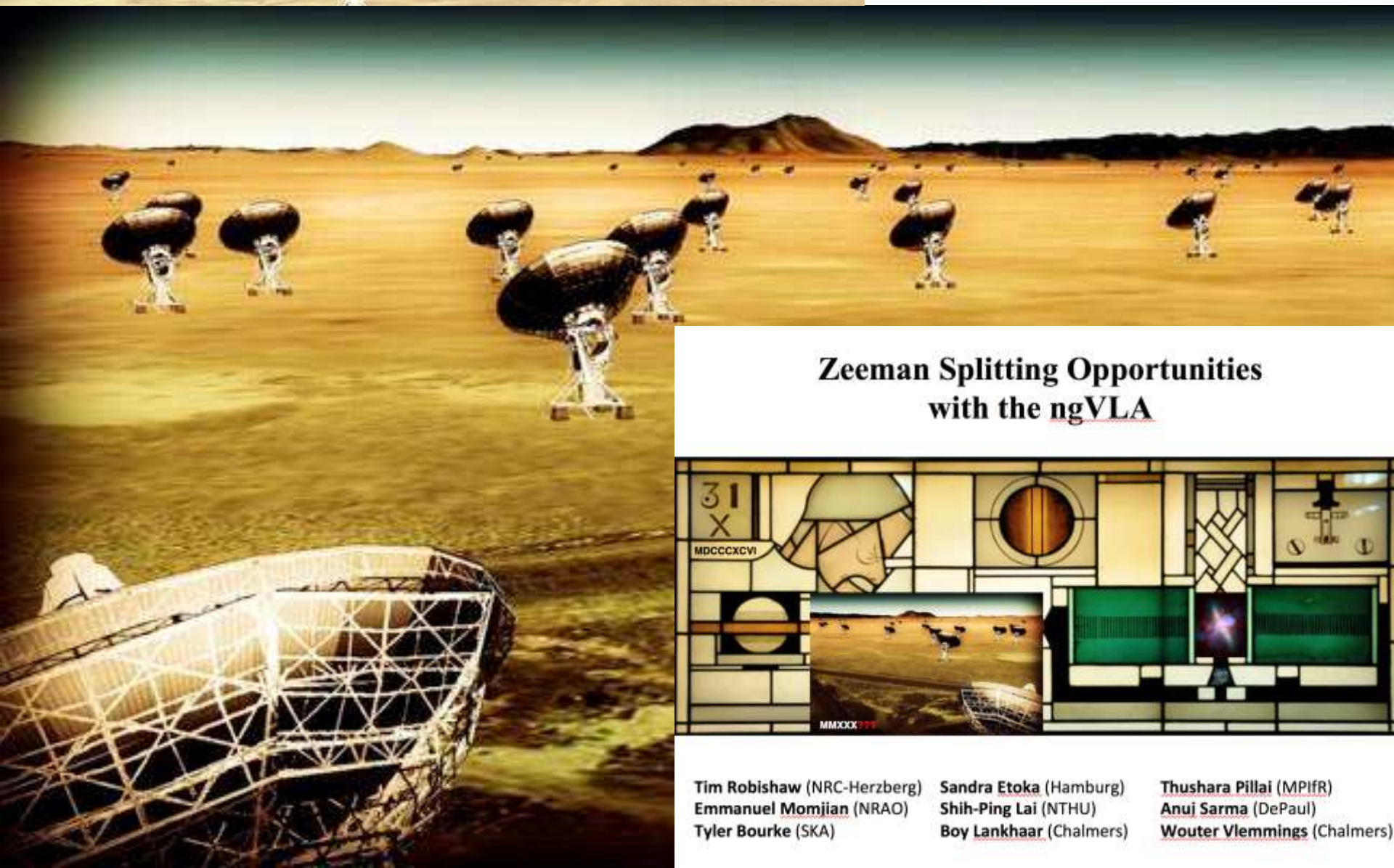
-ph.GA] 5 Mar 2015

Measuring Magnetic Fields Near and Far with the SKA via the Zeeman Effect

Timothy Robishaw*[1,†], James A. Green[2], Gabriele Surcis[3], Wouter Vlemmings[4], A. M. S. Richards[5], Sandra Etoka[6], Tyler Bourke[2], Vincent Fish[7], Malcolm Gray[5], Hiroshi Imai[8], Busaba Kramer[9], James McBride[10], Emmanuel Momjian[11], Anuj Sarma[12], Albert Zijlstra[5]



The ngVLA



Zeeman Splitting Opportunities with the ngVLA

Tim Robishaw (NRC-Herzberg)
Emmanuel Momjian (NRAO)
Tyler Bourke (SKA)
Sandra Etoka (Hamburg)
Shih-Ping Lai (NTHU)
Boy Lankhaar (Chalmers)
Thushara Pillai (MPIfR)
Anuj Sarma (DePaul)
Wouter Vlemmings (Chalmers)

The Magnificent Magnetic Mysterium Megamasers

- **77 OHMs searched.**
- **14 have Zeeman splitting detections.**
- **Median *B* field of 12 mG.**
  - **2-3 times larger than Galactic OH masers.**
- **Follow up:**
  - **Check for variability.**
  - **Rule out circularly polarized RFI.**
- **Want more VLBI observations of OHMs!**
  - **Can we map *B* in nearest OHMs?**
- **Want to extend sample outside of Arecibo range!**
  - **FAST**
  - **SKA**
  - **ngVLA**

M82



Ann Mao (MPIfR)





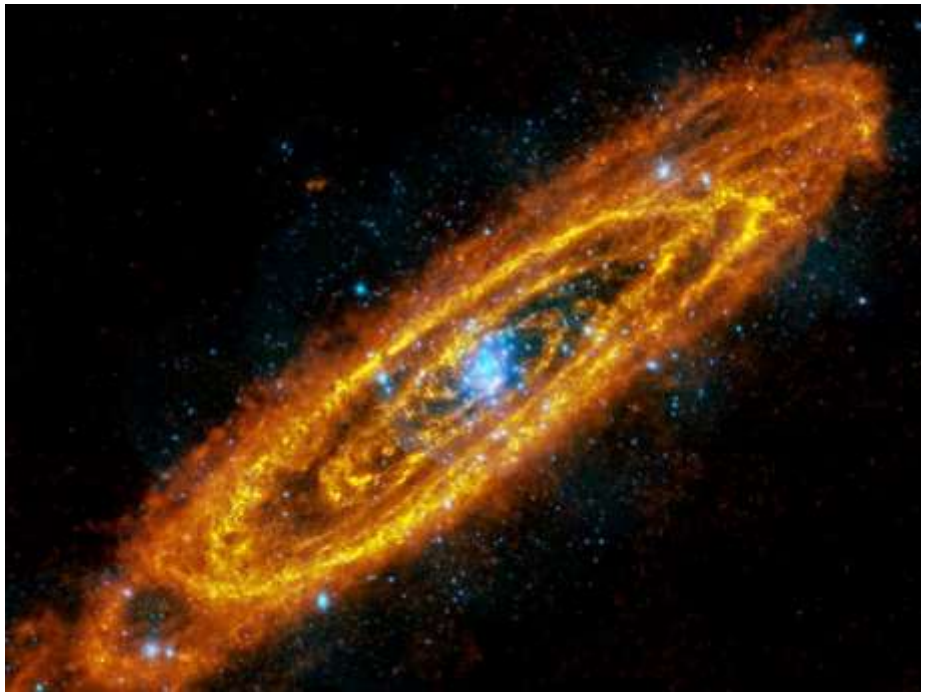
The JVLA

OH Masers in Nearby Galaxies

M31

Willett (2012) PhD work with VLA.

Found no OH masers to >10 mJy limit.



STOKES PARAMETERS

For a native linear feed, the observed Stokes parameters are created from appropriate combination of correlator auto- and cross-correlation spectra:

$$\mathbf{S}_{\rm obs} = \begin{bmatrix} I_{\rm obs} \\ Q_{\rm obs} \\ U_{\rm obs} \\ V_{\rm obs} \end{bmatrix} = \begin{bmatrix} XX_{\rm obs} + YY_{\rm obs} \\ XX_{\rm obs} - YY_{\rm obs} \\ 2XY_{\rm obs} \\ \pm 2YX_{\rm obs} \end{bmatrix}$$

For a native circular feed, the observed Stokes parameters would be:

$$\mathbf{S}_{\rm obs} = \begin{bmatrix} I_{\rm obs} \\ Q_{\rm obs} \\ U_{\rm obs} \\ V_{\rm obs} \end{bmatrix} = \begin{bmatrix} RR_{\rm obs} + LL_{\rm obs} \\ \pm 2LR_{\rm obs} \\ 2RL_{\rm obs} \\ RR_{\rm obs} - LL_{\rm obs} \end{bmatrix}$$

"When signs are involved, even two Dutch physicists as scrupulous as Lorentz and Zeeman may make errors." **--EMILIO SEGRE, 1976**

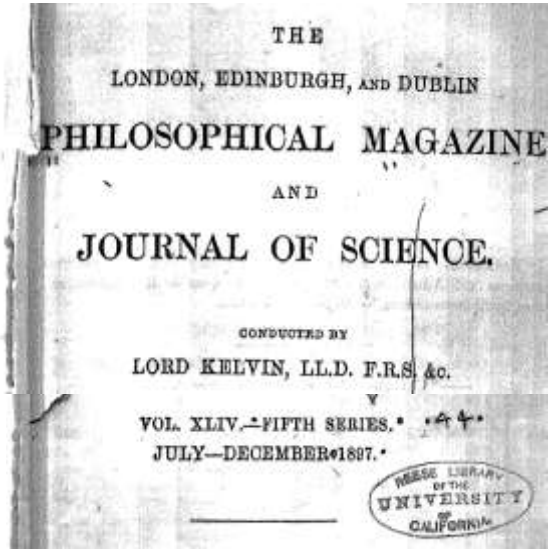
THE
ASTROPHYSICAL JOURNAL
AN INTERNATIONAL REVIEW OF SPECTROSCOPY
AND ASTRONOMICAL PHYSICS

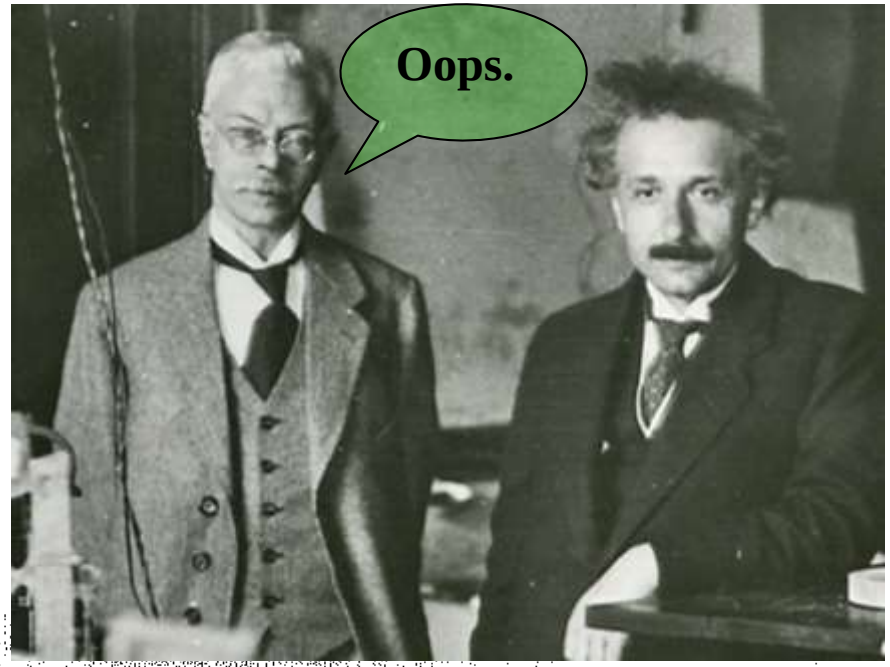
1897 ApJ Vol 5

24. It may be deduced from the experiment of § 20 whether the positive or the negative ion revolves.

If the lines of force were running towards the gratings, the right-handed circularly polarized rays appeared to have the smaller period. Hence in connection with § 18 it follows that the positive ions revolve, or at least describe the greater orbit.

"When signs are involved, even two Dutch physicists as scrupulous as Lorentz and Zeeman may make errors." --EMILIO SEGRE, 1976


THE
LONDON, EDINBURGH, AND DUBLIN
PHILOSOPHICAL MAGAZINE
AND
JOURNAL OF SCIENCE.
CONDUCTED BY
LORD KELVIN, LL.D. F.R.S. &c.
VOL. XLIV.—FIFTH SERIES.
JULY—DECEMBER 1897.

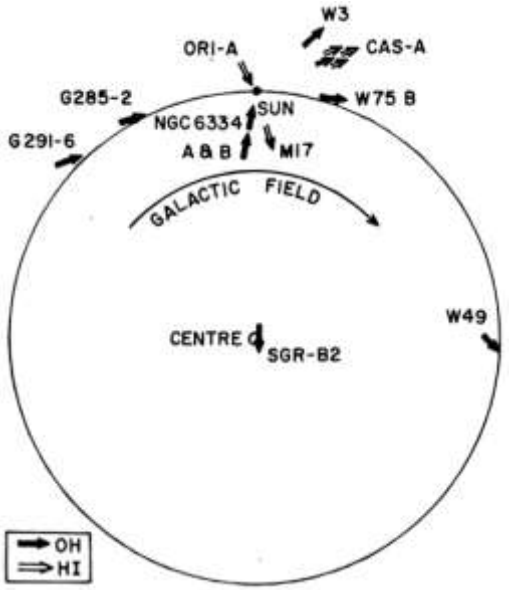


* *C. R.* 1897, t. cxxiv. pp. 748 & 242.

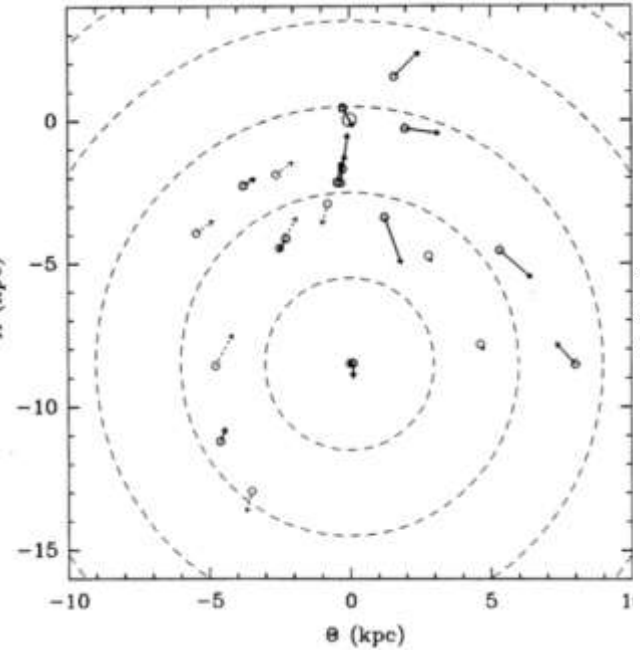
† The sign of the circular polarization is the same in the case of this cadmium line and of the D-lines. I must, however, correct my statement in § 24 of my former paper. I now see that if the lines of force are running towards the grating, the right-handed circularly polarized rays appear to have the greater period. Hence the radiation is due chiefly to the motion of a *negatively*-charged particle. Probably my mistake arose from a faulty indication of the axis of the λ/4-plate used.

OH Masers in the Milky Way

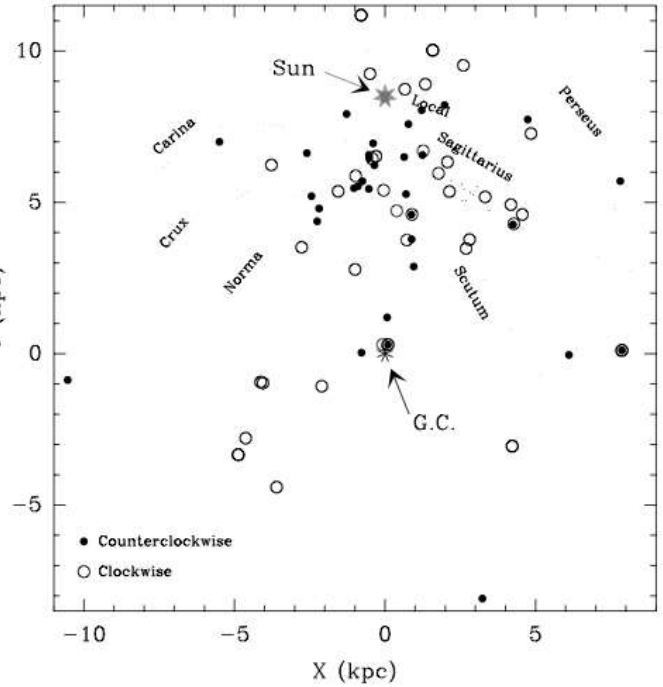
Davies (1974)

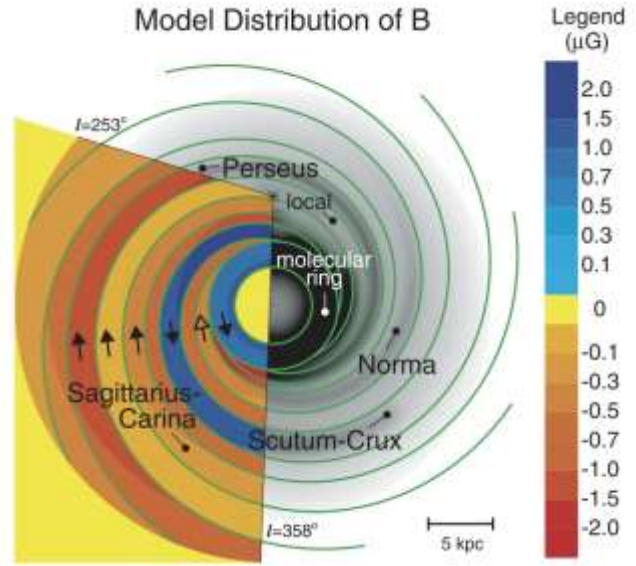


Reid & Silverstein (1990)



Fish et al. (2003)

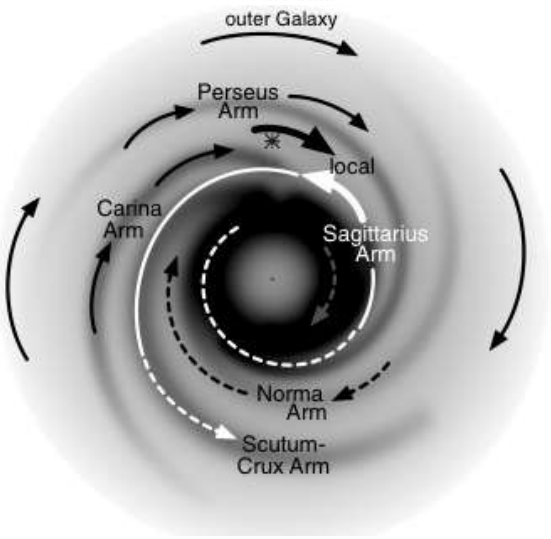




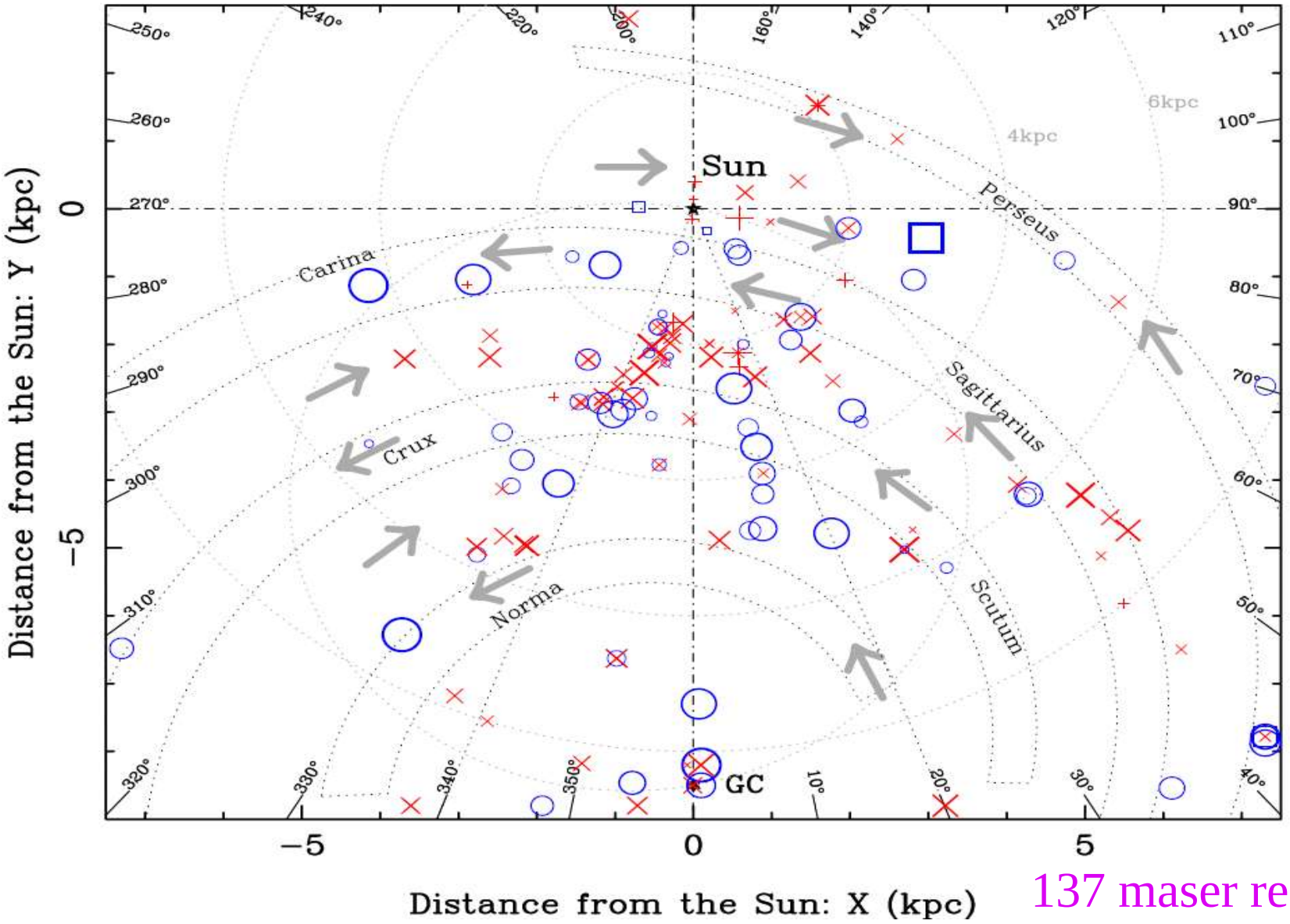
Brown et al. (2007)

Rotation Measures

van Eck et al. (2011)



OH Masers As Tracers of Galactic Field



137 maser regions

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



MAGMO:
THE MAGNETIC FIELDS OF THE MILKY WAY THROUGH OH MASERS

Jimi Green (CSIRO)



CABB: Compact Array Broadband Backend

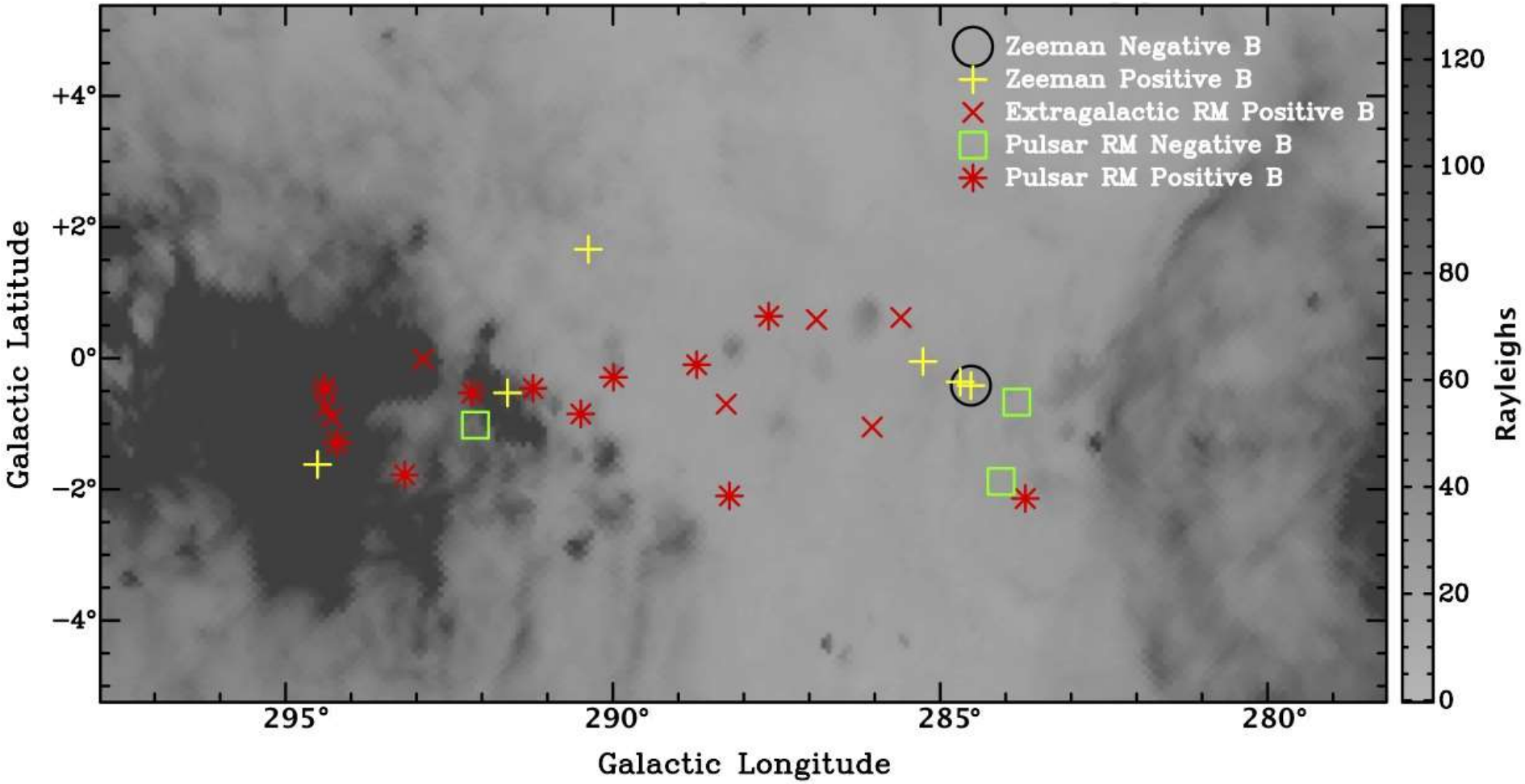


The MAGMO project

First Results (Green et al. 2012 MNRAS 425 2530)

- 23 sites of maser emission across six regions of star





Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS 440, 2988–2996 (2014) doi:10.1093/mnras/stu429

A quantum mechanical approach to establishing the magnetic field orientation from a maser Zeeman profile

J. A. Green,[1,2★] M. D. Gray,[3] T. Robishaw,[4] J. L. Caswell[2] and N. M. McClure-Griffiths[2]

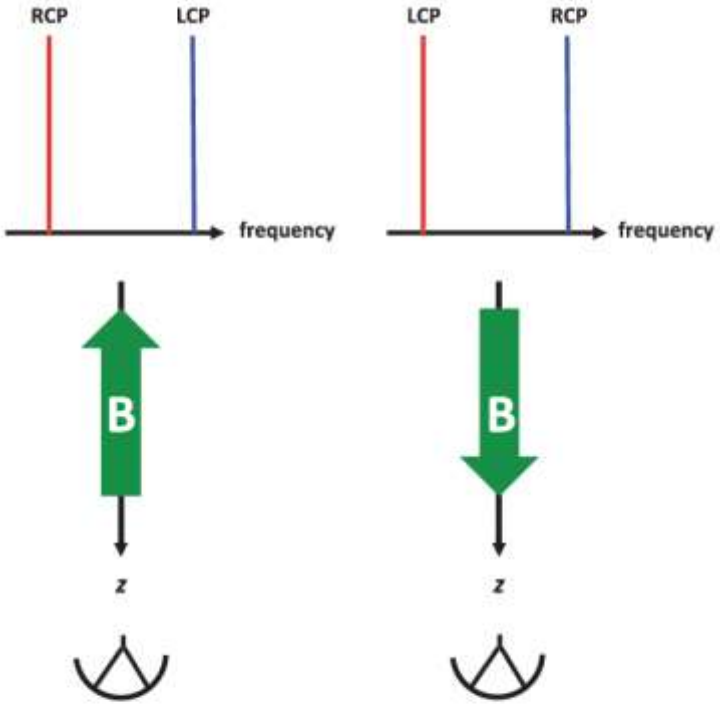
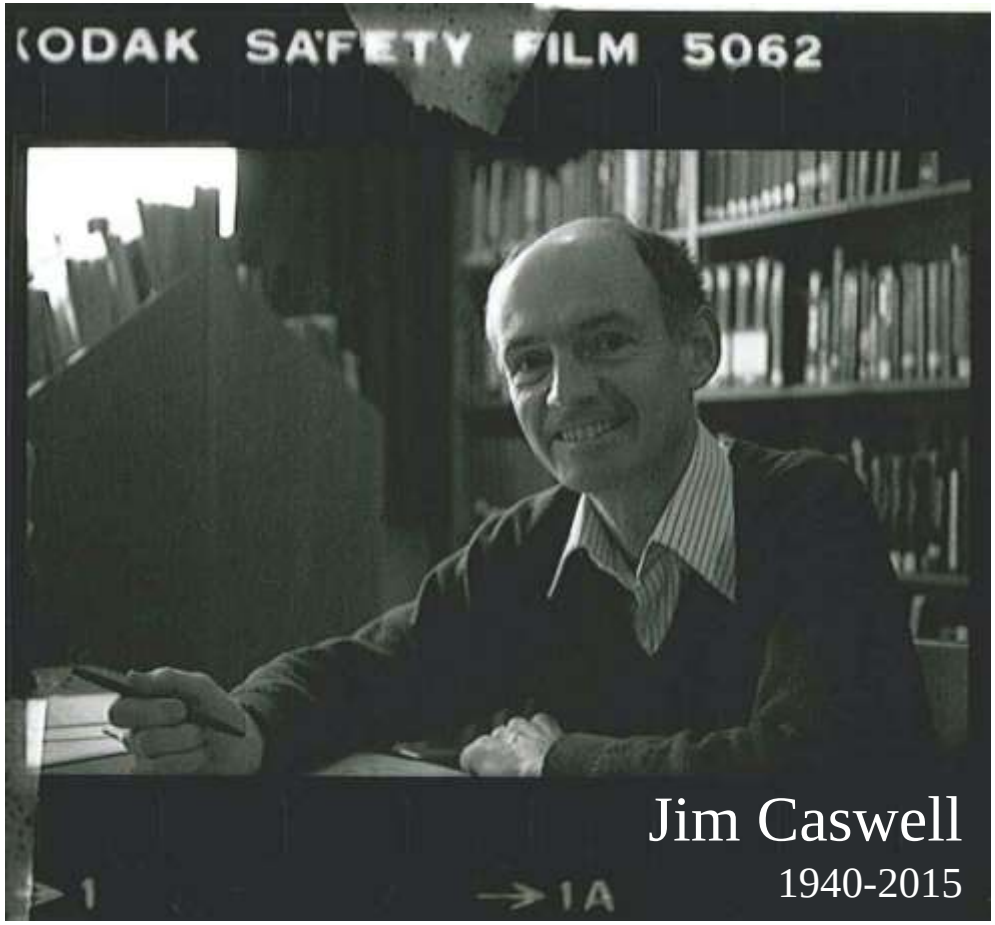


Figure 5. Summary of observed Zeeman profiles (top) and corresponding magnetic field directions relative to the observer (bottom). The IAU definition of Stokes *V* and the IEEE definition of polarization handedness are assumed. Frequency increases from left to right.







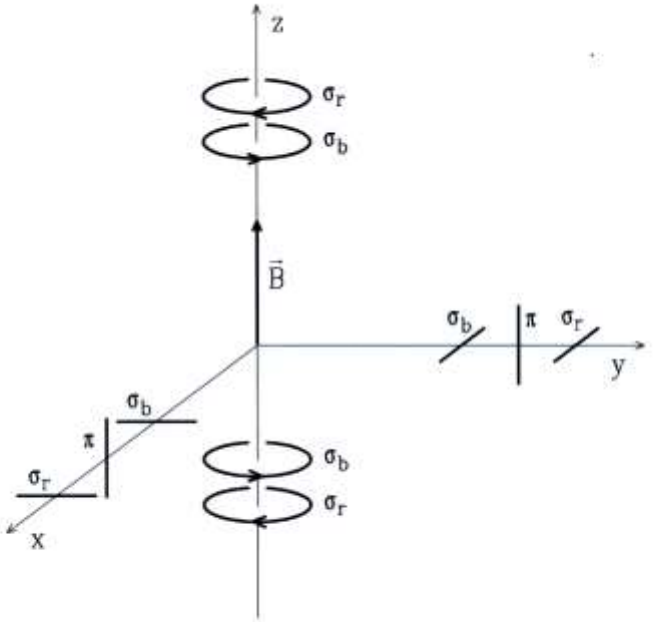


Fig.3.1. The polarization properties of the radiation emitted by different Zeeman components depend on the type of component and on the angle between the observing direction and the magnetic field vector. For the radiation emitted along the x, y, and z-axes, the tip of the wave electric field vector draws, in a fixed point, the figures here shown.

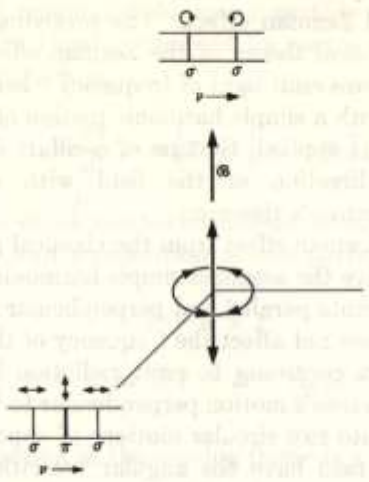
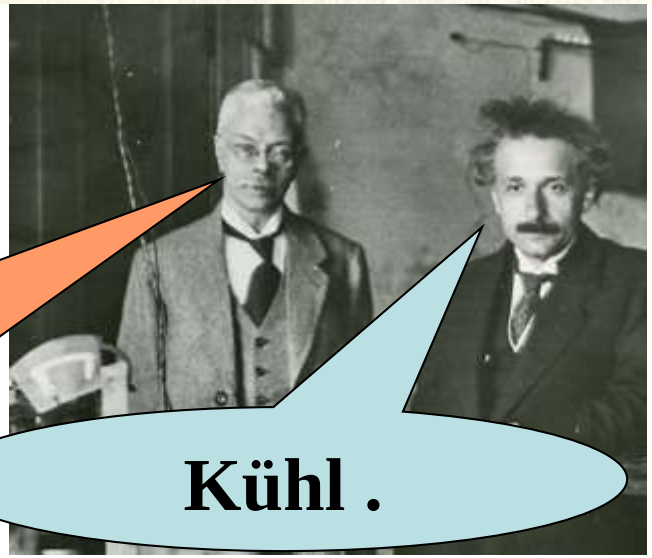


FIG. 10–5. Polarization of light in the spectral lines produced by the Zeeman effect.

It's easy, Einstein!
π = parallel
σ = senkrecht



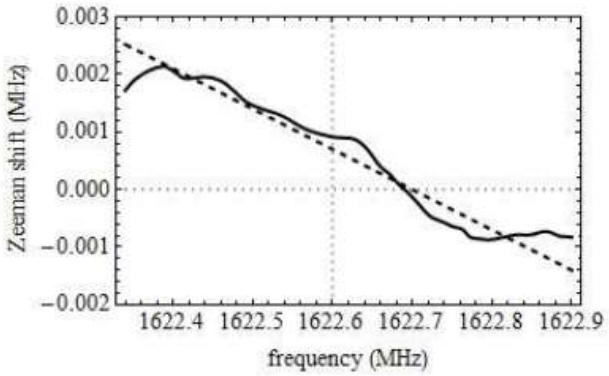
Kühl .

Using the Antiderivative of the Stokes V Profile to Analyze Magnetic Fields in the Interstellar Medium

Sadie Moore, Ken Gayley, and Tim Robishaw
University of Iowa and Dominion Radio Astrophysical Observatory

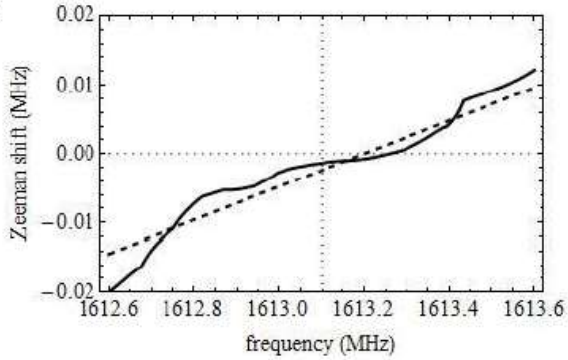
$$G(\nu) = \frac{b}{2}\langle B \rangle \left(I(\nu) - I_c \right)$$





$\rho_z = 9.7 \times 10^{-17}\, g/cm^3$
$m = -0.007$
$B_o \cos\theta = 440\,\mu G$
$\rho > 5 \times 10^{-21}\, g/cm^3$

Fig. 2. OH megamaser emission (Robishaw et al. 2008) from IRAS F01417+1651 III Zw 35). Their field estimate is also about double this one.



$\rho_z = 9.7 \times 10^{-17}\, g/cm^3$
$m = +0.024$
$B_o \cos\theta = 1.5 mG$
$\rho > 5 \times 10^{-20}\, g/cm^3$

Fig. 3. OH megamaser emission (Robishaw et al. 2008) from IRAS F10038-3338 (IC 2545). Their field estimates are comparable or a bit higher.