Synchrotron emission from molecular clouds

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There isn't any, right?

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There isn't any, right?

Disclaimer: everything in this talk is mega-preliminary!

The idea : (& the puzzle which led to this work)

In molecular clouds:

Magnetic field **B**, gas density n

Observations show:

$$\mathbf{B} \sim n^{0.5}$$

But

$$\text{synchrotron} \sim \mathbf{B}^2$$

$$\rightarrow \quad \text{synchrotron} \sim n$$

Integrated over line-of-sight

$$I(\text{synchrotron}) \sim N(H) \quad \text{gas column density}$$

Molecular clouds should shine in synchrotron!

→ The synchrotron sky should resemble the CO sky!

Synchrotron map shows no obvious sign of molecular gas.

Little resemblance to CO map.

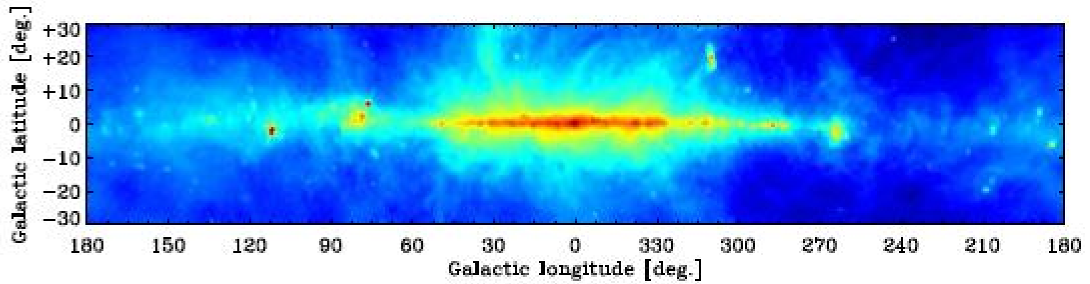
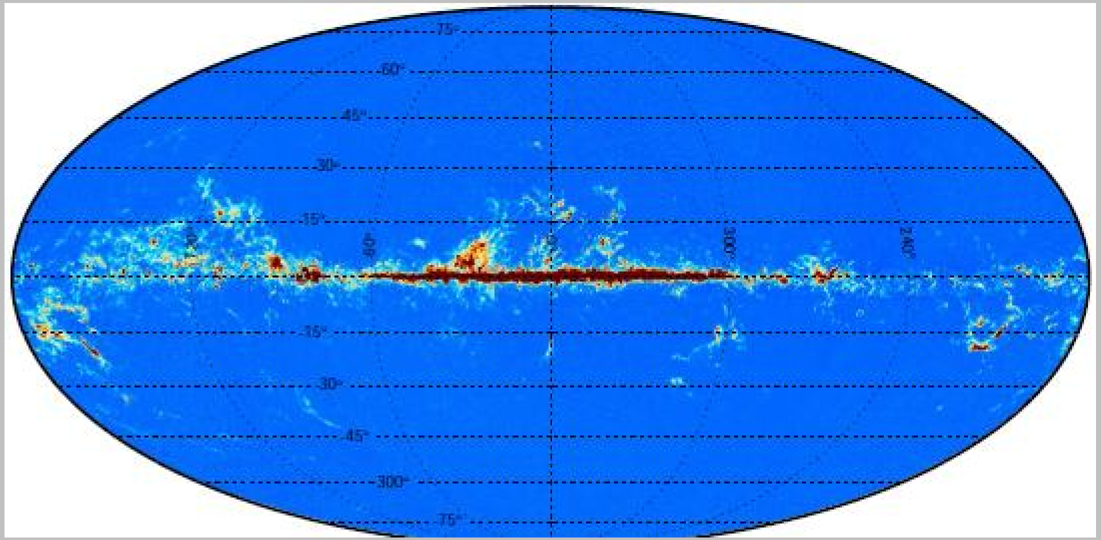


Figure 10. The Galactic plane as seen at 408 MHz (Haslam et al. 1982). The map is in cartesian projection and is centred at $(l, b) = (0^\circ, 0^\circ)$. The latitude range covers $|b| < 30^\circ$ and the graticule spacing is 20°. The colour scale is logarithmic from the map minimum (11 K) and a maximum of 1000 K.

408 MHz
Haslam



^{12}CO, Planck

Correct 408 MHz for free-free emission

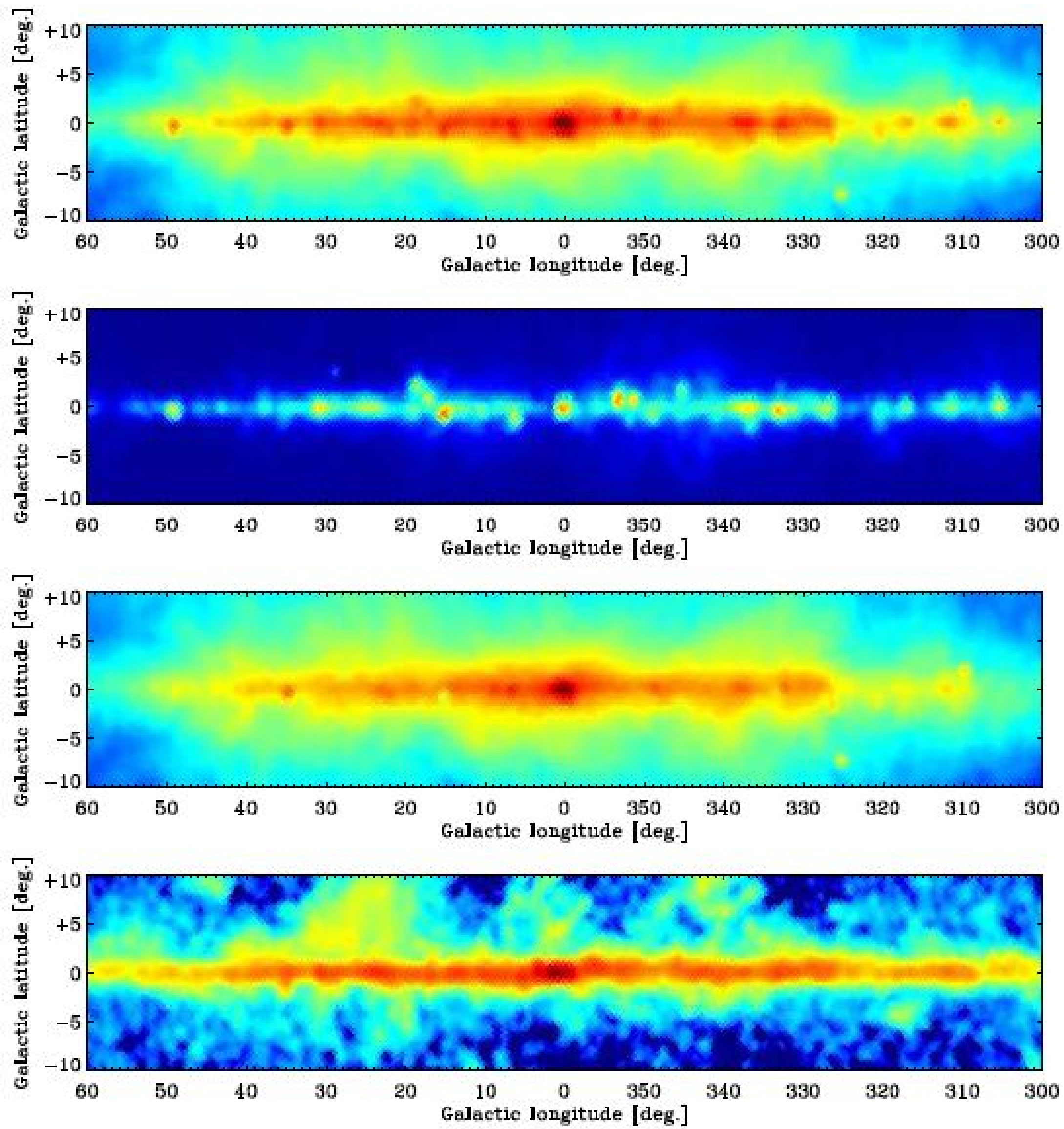


Figure 3. Maps of the inner Galactic plane. From *top* to *bottom*: i) Haslam et al. (1982) 408 MHz map; ii) WMAP 9-year MEM free-free map, scaled to 408 MHz; iii) Synchrotron map at 408 MHz by subtracting the free-free model from the 408 MHz map; iv) *Planck* CO Type 1 intensity map. The maps are in Cartesian project centred at $(l, b) = (0^\circ, 0^\circ)$ and cover a latitude of $l = 60^\circ \rightarrow 0^\circ \rightarrow 300^\circ$ and $|b| < 10^\circ$. The colour-scales are logarithmic.

408 MHz
Haslam

free-free
WMAP MEM

408 MHz
minus
extrapolated free-free

no obvious
correlation

^{12}CO, Planck

NB 408 MHz includes SNR etc. which would disturb a correlation with CO

From Zeeman effect Crutcher (2012)

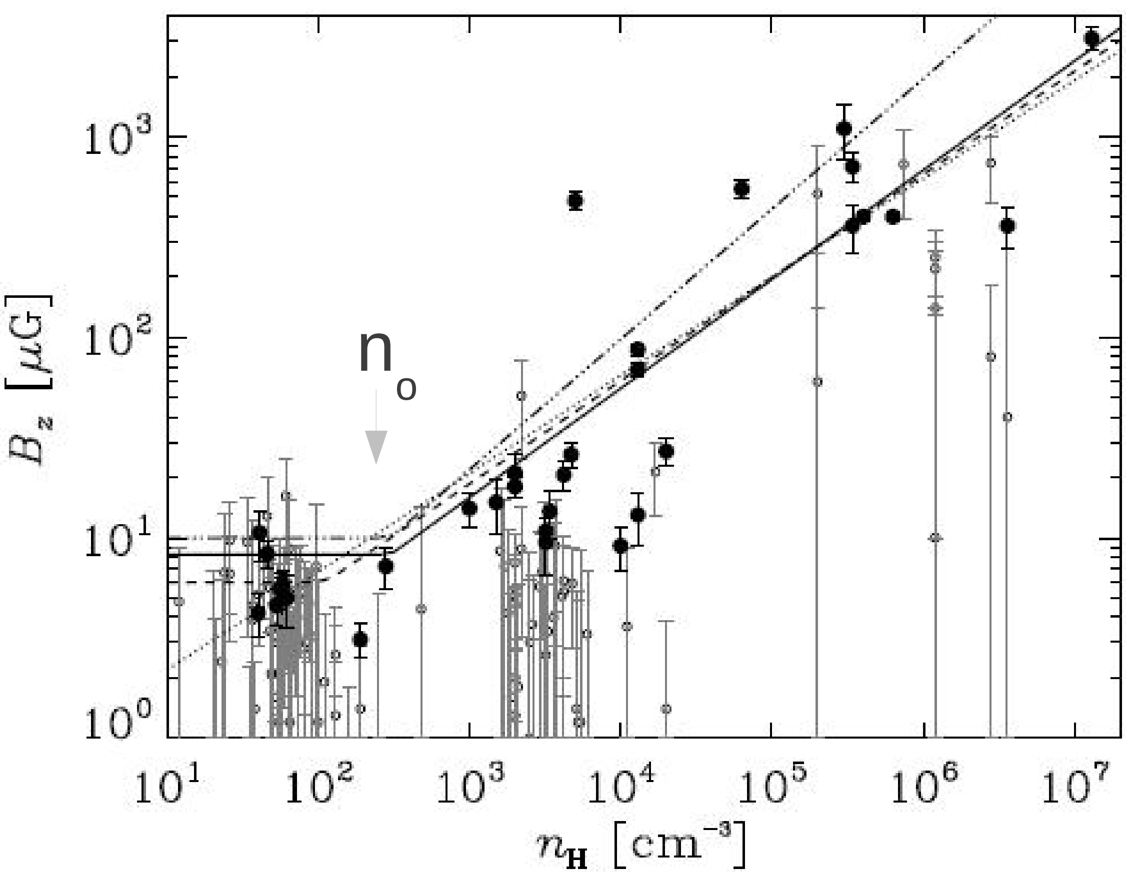


Figure 1. Magnetic field strengths B_z as measured by Zeeman splitting experiments against gas density for a sample of molecular clouds. Significant detections ($> 3\sigma$) are plotted as black and filled circles. Data taken from Crutcher et al. (2010). The lines represent fits to the significant data points: i) constant B_0 for $n_{\rm H} < 300\,{\rm cm}^{-3}$ and power-law for $n_{\rm H} > 300\,{\rm cm}^{-3}$ (*solid line*), ii) a power-law for $n_{\rm H} > n_0\,{\rm cm}^{-3}$ (*dashed line*), iii) a power-law for all $n_{\rm H}$ (*dotted line*), and iv) the fit by Crutcher et al. (2010) with $B_0 = 10\,\mu{\rm G}$, $n_0 = 300\,{\rm cm}^{-3}$ and $\kappa = 0.65$ (*triple dot-dashed line*).

$B = B_o \quad (n < n_o)$

$B = B_o\,(n / n_o)^\kappa \quad (n > n_o)$

From Zeeman effect e.g. Crutcher (2012)

$$B = B_o \qquad (n < n_o)$$

$$B = B_o \, (n / n_o)^{\kappa} \qquad (n > n_o)$$

$$\kappa = 0.67$$

$$n_o = 300 \text{ cm}^{-3}$$

So effect is smaller than naive expectation.

Using B-field
and
cosmic-ray models

Cosmic- ray electron distribution

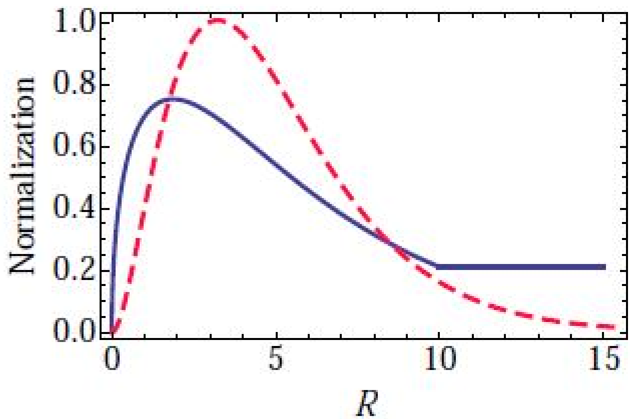
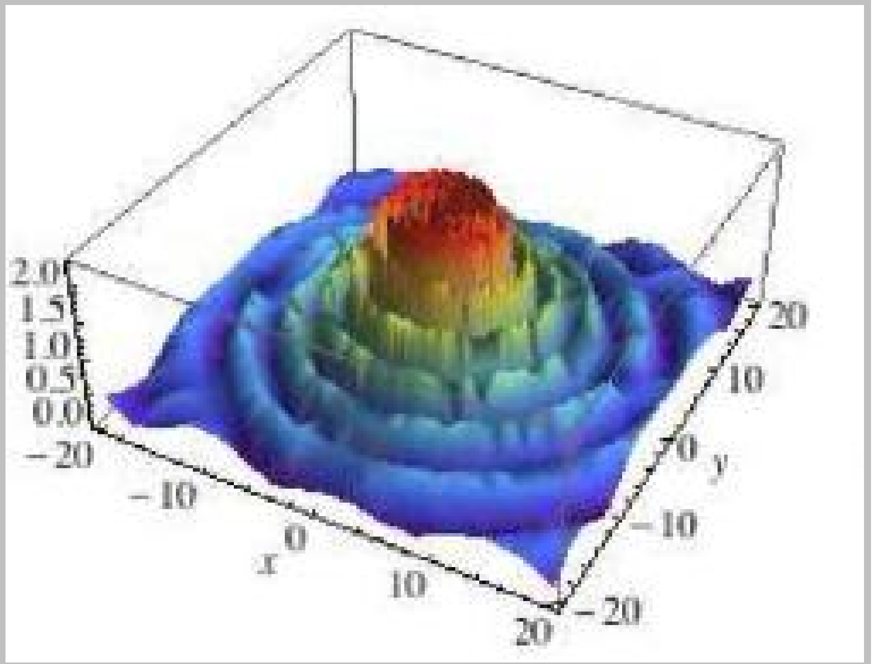


Figure 10. CR source distributions from Strong et al. (2010) (blue line) and pulsar-based Lorimer et al. (2006) (red dashed line). R is the Galactocentric radius in kpc. The distributions are normalized at $R = 8.5$ kpc.

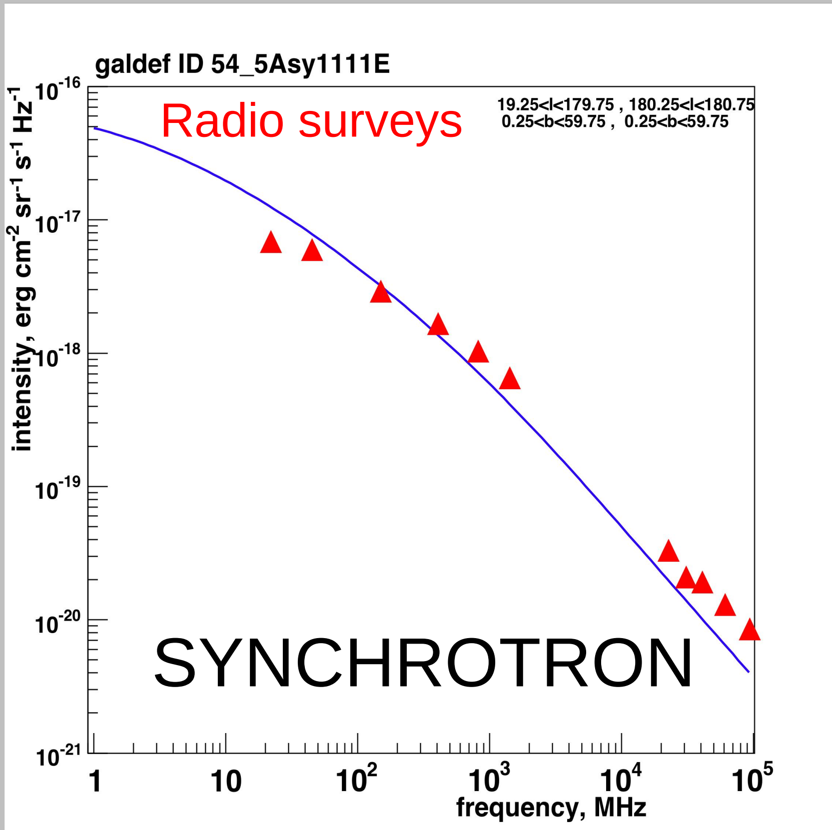
B model

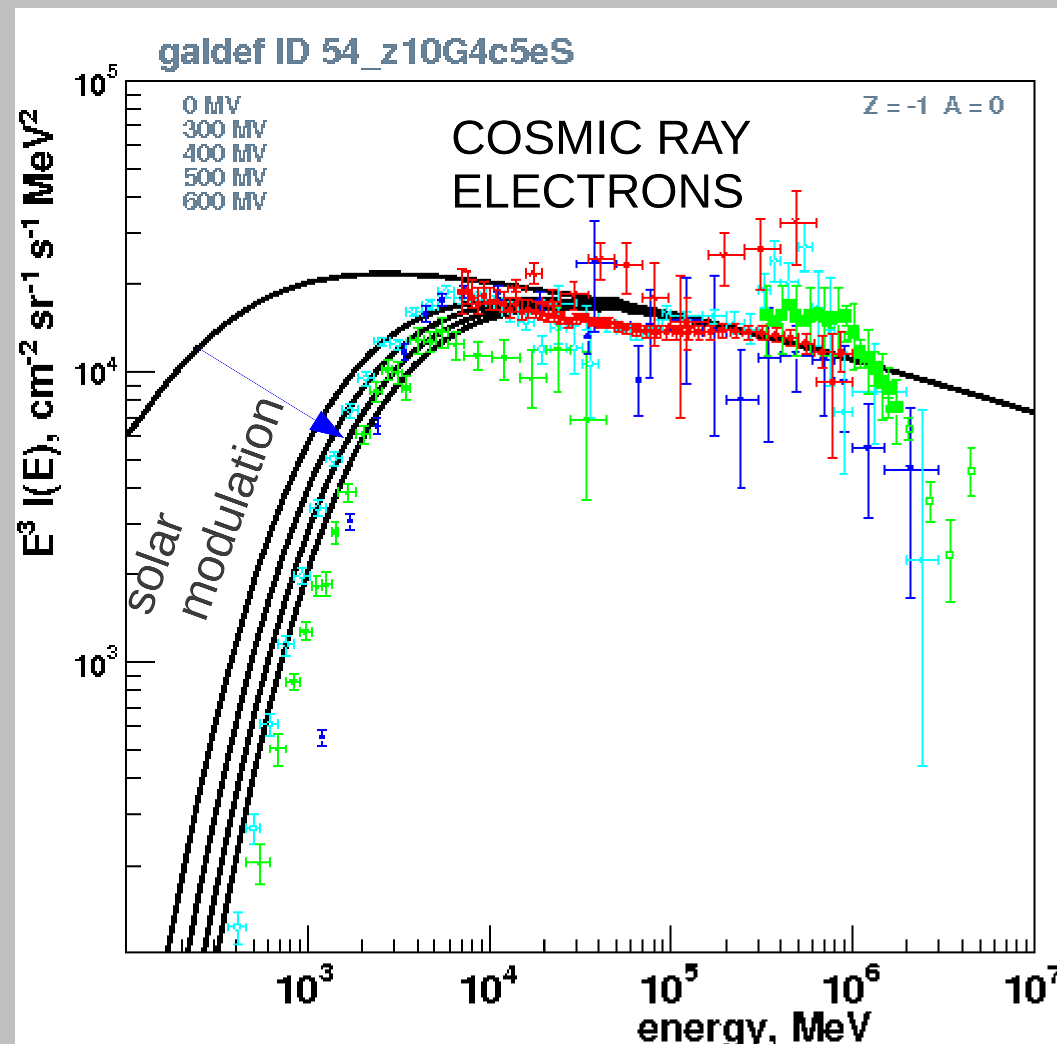


Orlando&Strong MNRAS 436, 2127 (2013)

Electron + positron spectrum

> 7 GeV : Fermi-LAT



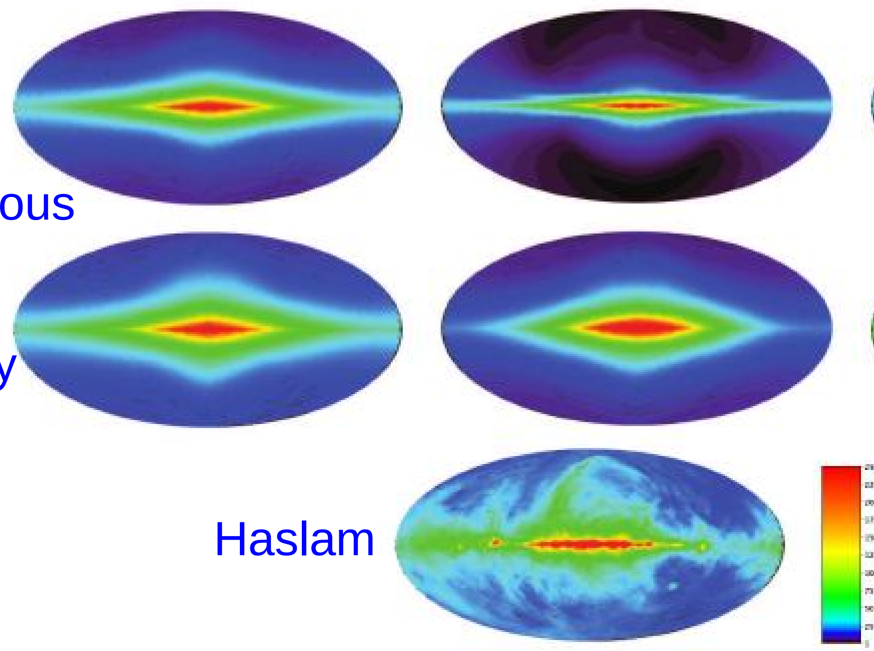


Using **B** model and cosmic-ray electron distribution

408 MHz

Interstellar radio emission 19

Using various B-field and cosmic-ray models



Haslam

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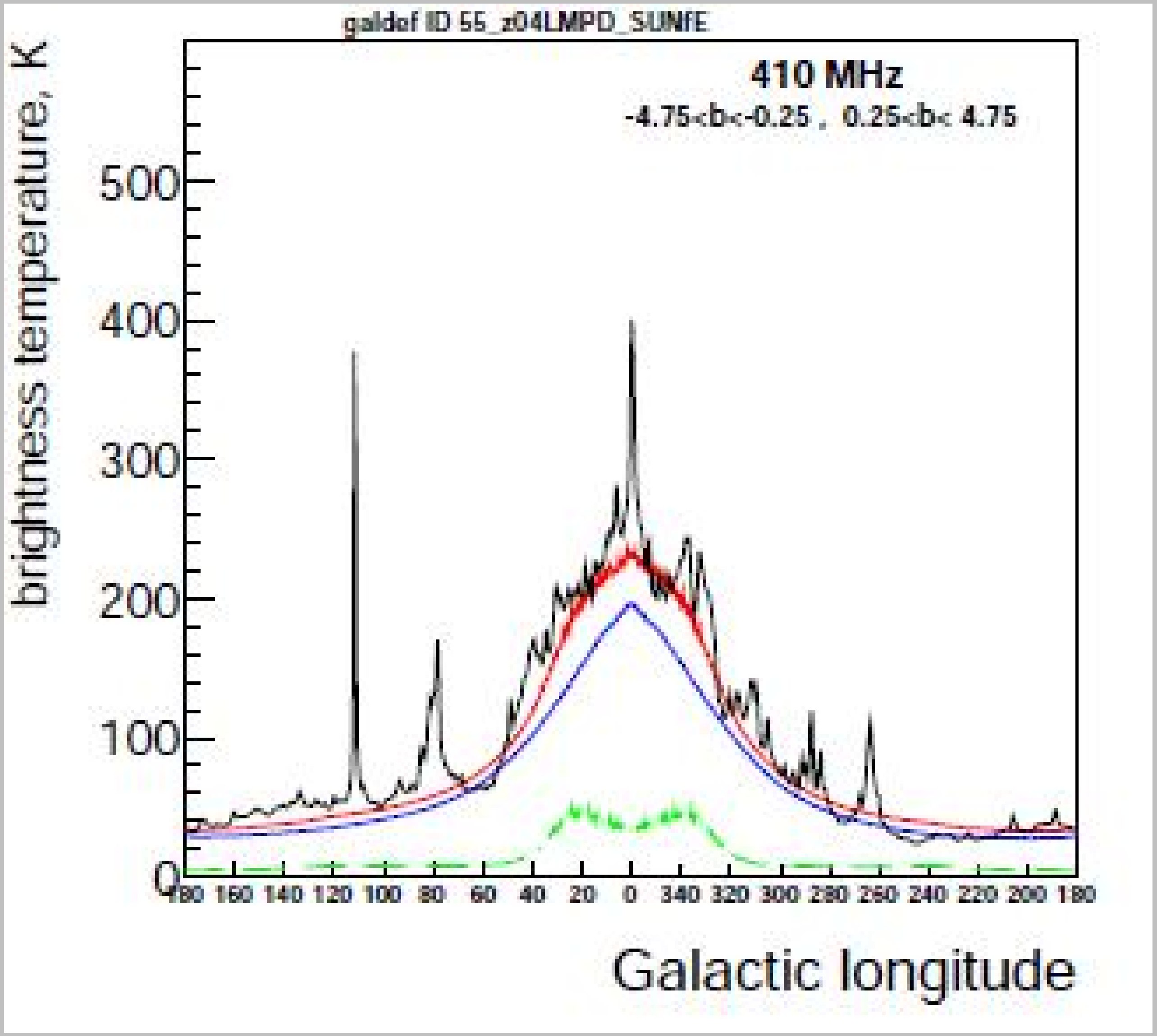
408 MHz

Using
B-field
and
cosmic-ray
model



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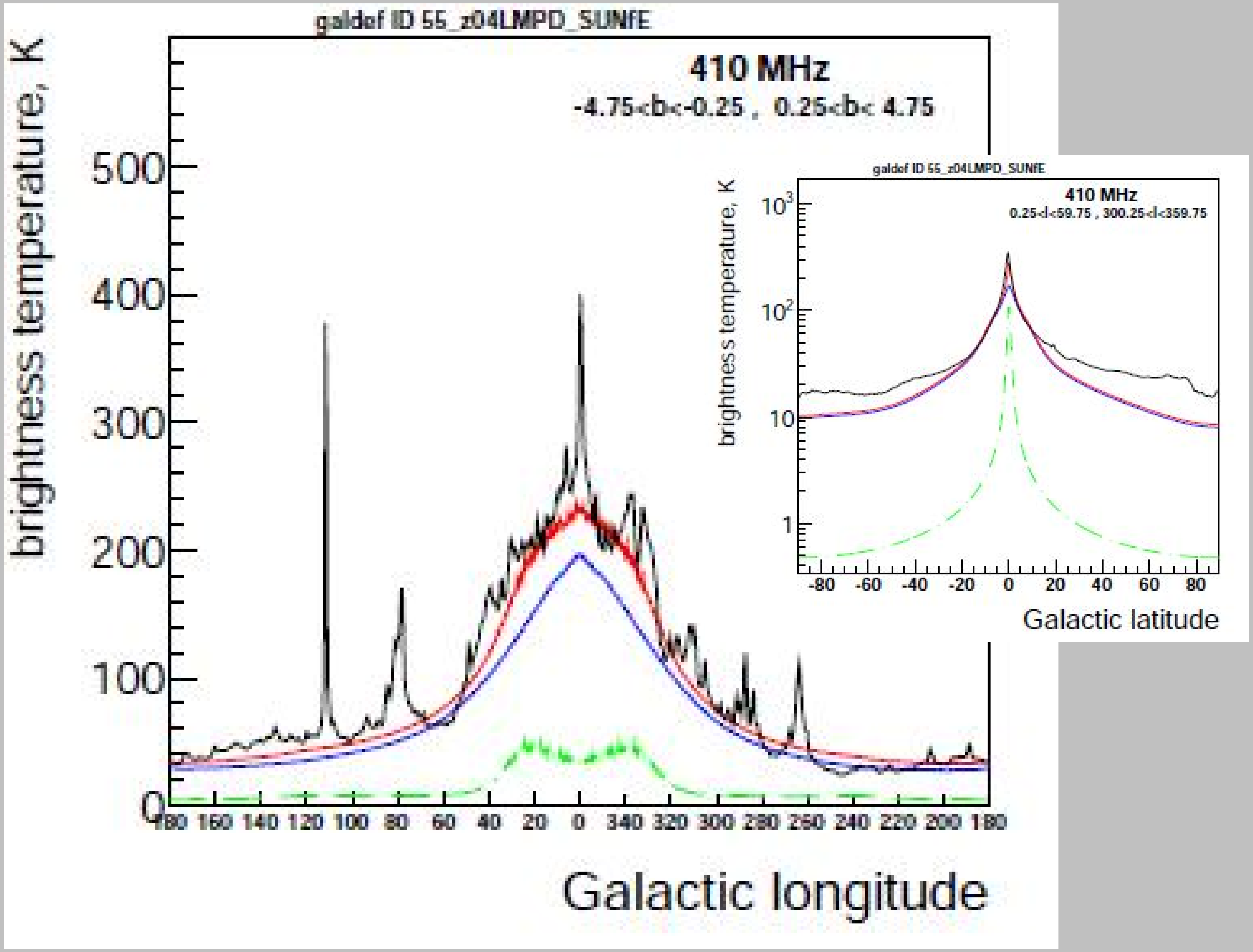
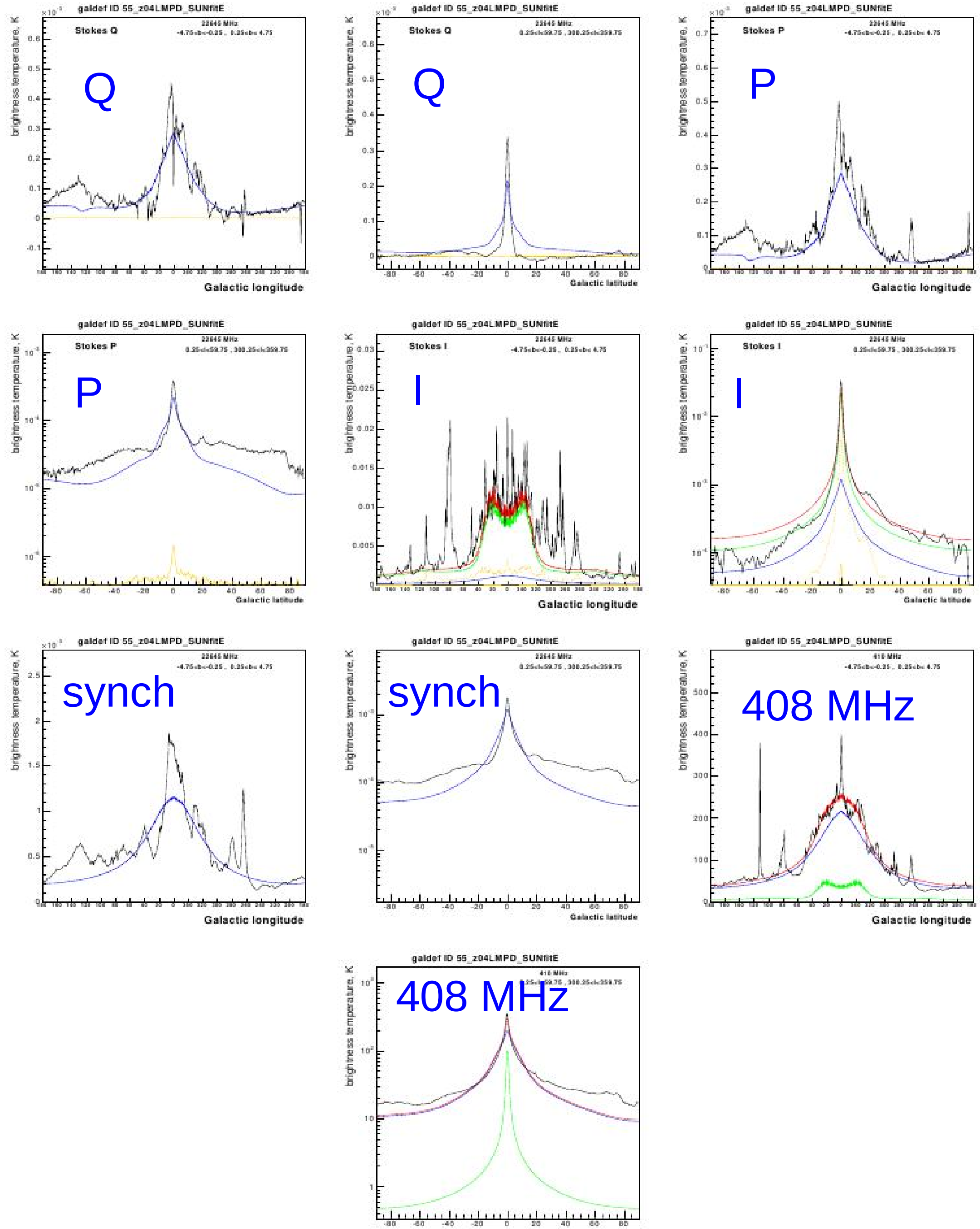
408 MHz

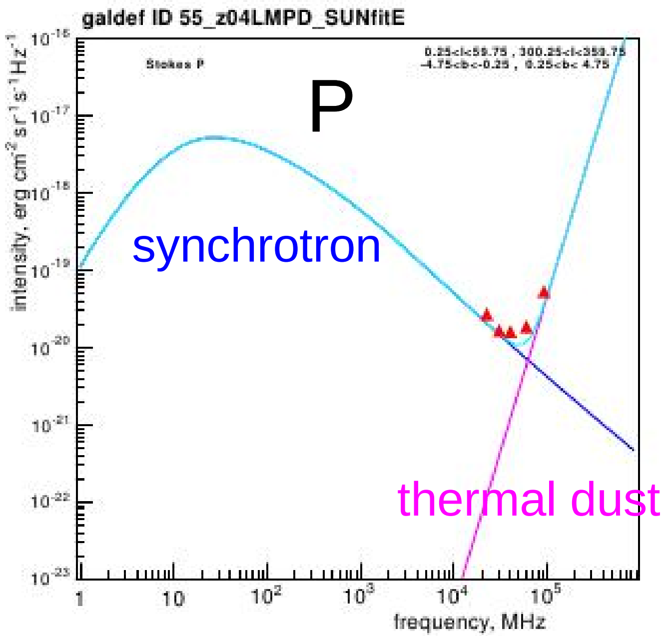
Using various
B-field
and
cosmic-ray
models

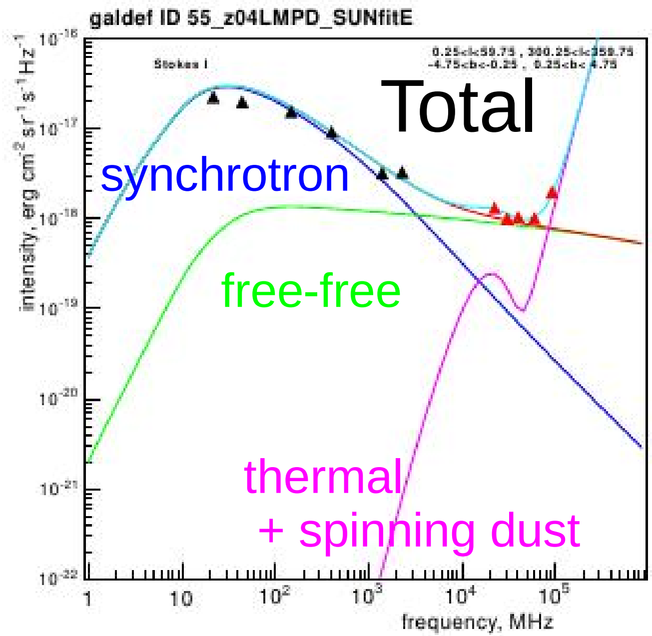


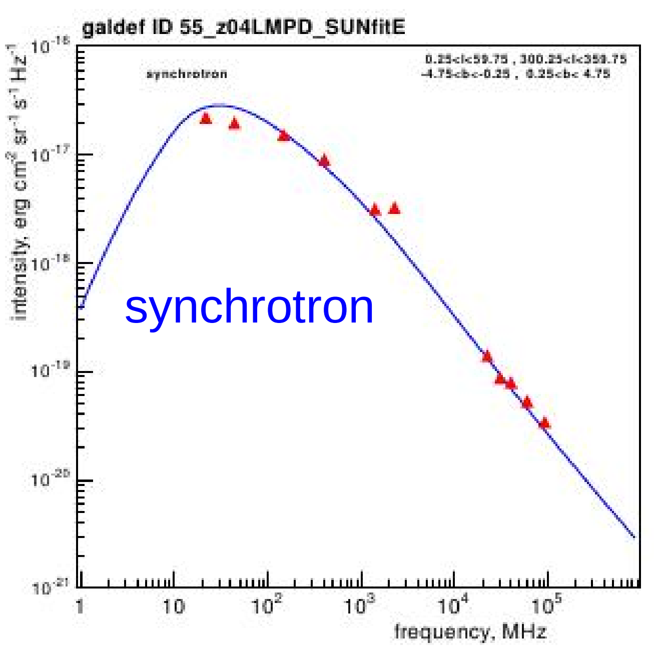
Orlando&Strong MNRAS 436, 2127 (2013)



Orlando&Strong MNRAS 436, 2127 (2013)







INNER GALAXY

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408 MHz compared to HI, CO

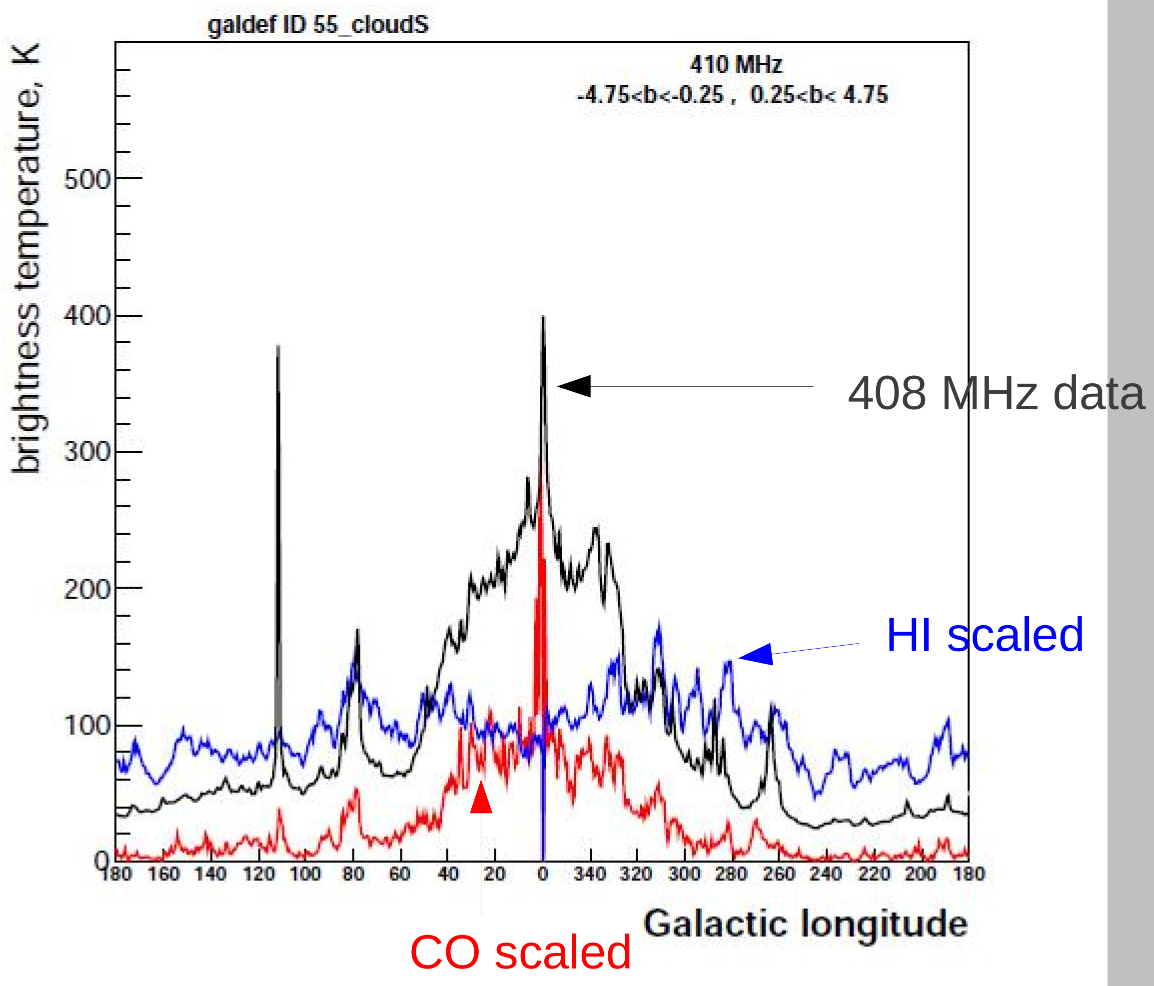


Figure 4. The Galactic plane as seen at 408 MHz (Haslam et al. 1982) (black curve). Red curve: scaled CO; blue curve: scaled HI. The latitude range covers $|b| < 5°$.

CO scaled to 408 MHz

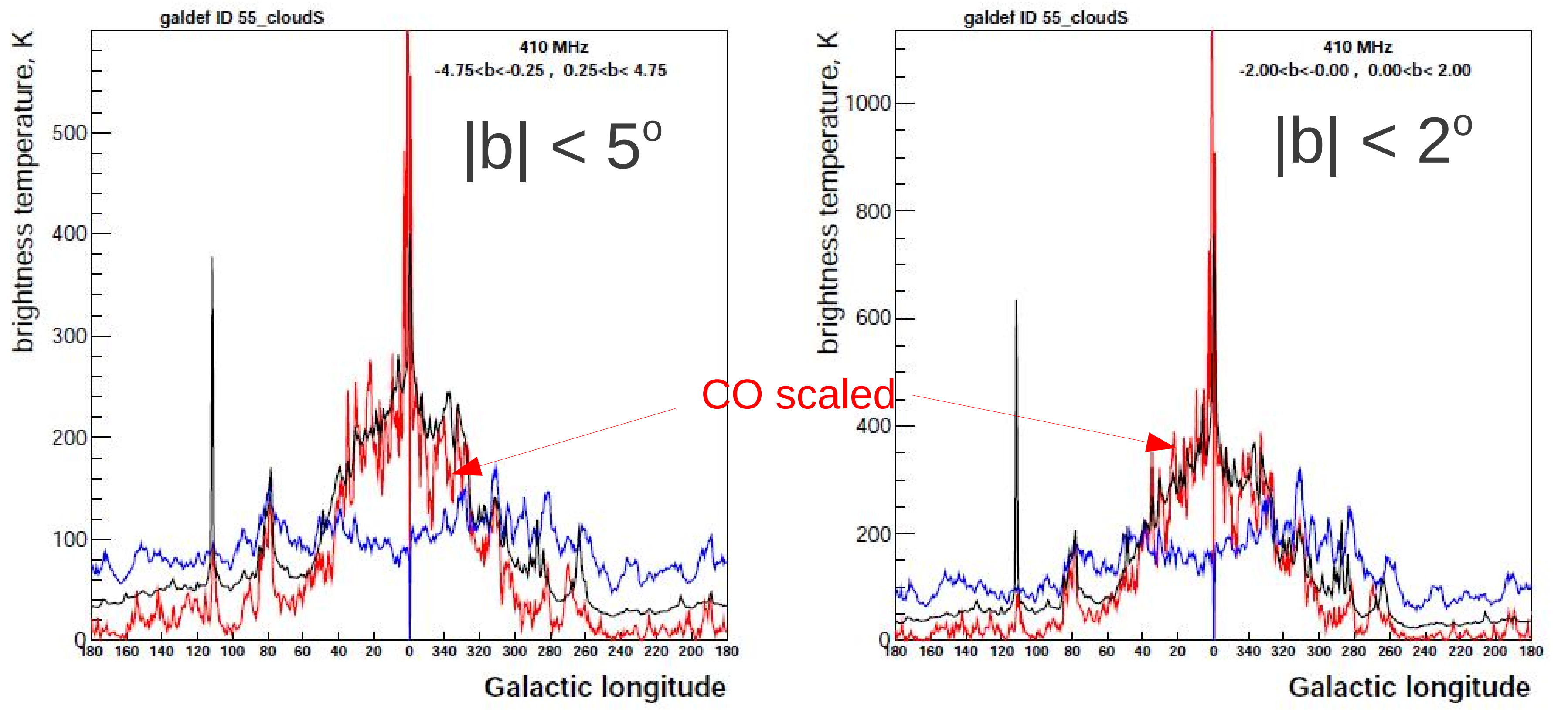
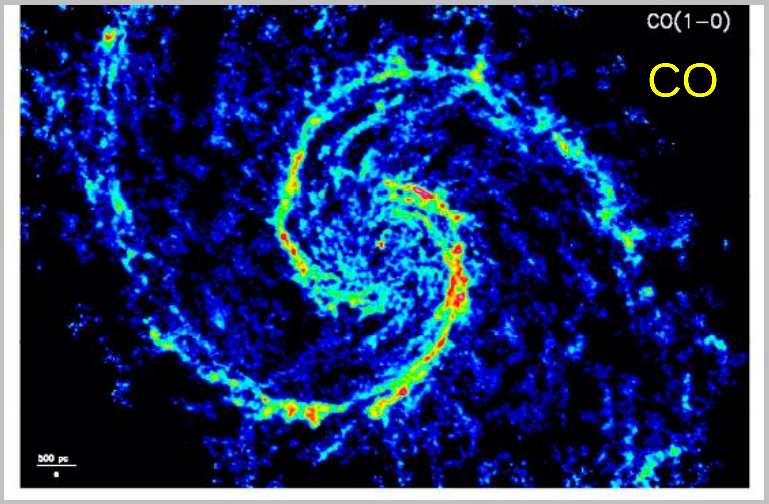


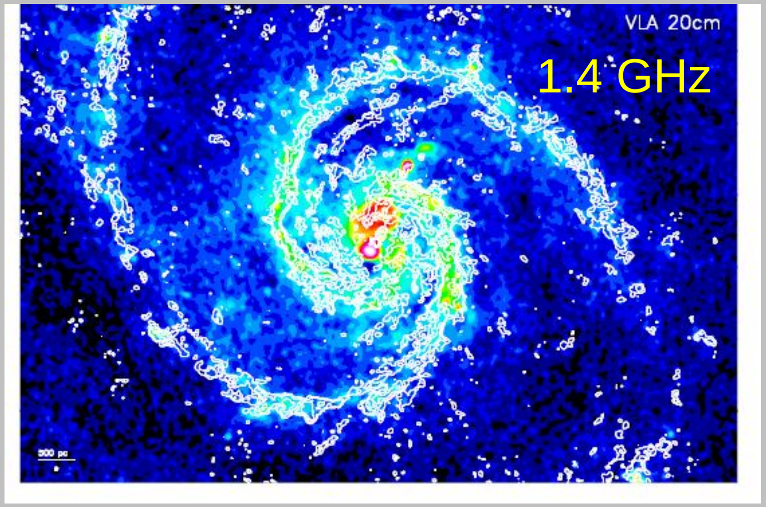
Figure 5. The Galactic plane as seen at 408 MHz (Haslam et al. 1982) (black curve). Red curve: scaled CO to fit data; blue curve: scaled HI (original scaling). Latitude range covers $|b| < 5°$ (*left*) and $|b| < 2°$ (*right*).

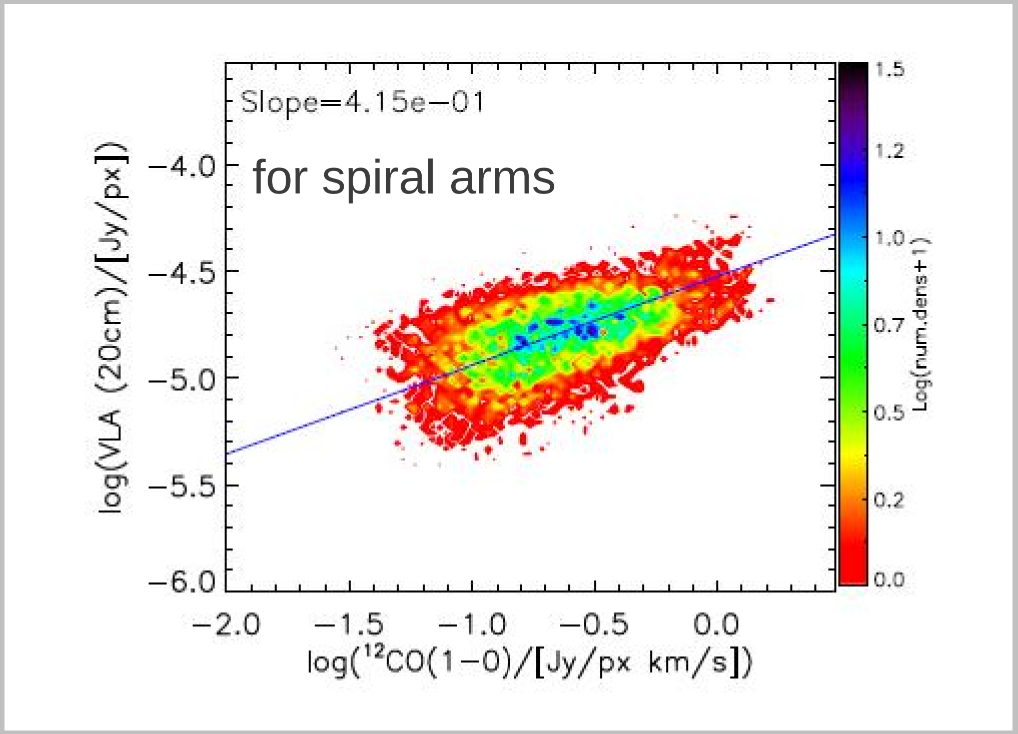
In fact synchrotron *does* correlate with CO along plane in inner Galaxy.
Including peak at Galactic Centre.
But what does this mean?
NB Cosmic-ray electron distribution not included in this scaling, would improve fit.

Perhaps clouds make significant contribution to synchrotron in Galactic plane.
Then they should be included in large-scale models.

External galaxies: Schinnerer et al 779, 42 (2013)
M51
3“ resolution (~120 pc)
1.4 GHz vs CO
They suggest correlation could be related to B(n)







Clouds do shine
in synchrotron

Cosmic-ray electrons (and positrons)

1 – 100 GeV for GHz synchrotron
Do these leptons penetrate clouds? … sure they do!?

Gamma rays from clouds show that GeV protons do, and momentum which controls propagation is same as for leptons.

(also a theme at this conference, but issue mainly at MeV energies)

Secondary electron / positron production in clouds via pions :
Jones, Protheroe & Crocker PASA 25, 161 (2008)
Protheroe etal MNRAS 390, 683 (2008)
This would further increase the synchrotron.

Individual clouds

Individual clouds have not been detected as synchrotron sources.

Jones, Protheroe & Crocker PASA 25, 161 (2008) :
upper limits on B ($< 500\ \mu G$) for two starless cores.
still consistent with B(n) law.

Jones etal ApJ 141, 82 (2011) : no synchrotron from SgrB region, apart from one source.

From Zeeman effect e.g. Crutcher (2012)

$$B = B_o \qquad (n < n_o)$$

$$B = B_o\,(n / n_o)^{\kappa} \qquad (n > n_o)$$

$$\kappa = 0.67$$

$$n_o = 300\ \mathrm{cm}^{-3}$$

Significant synchrotron only from dense cores, sub-parsec, arcsec scales
But still it is there at some level, can we exploit it?

Potential probe of B in clouds.
Detects total B not just line-of-sight
Detects integrated emission, not just densest regions.

Zeeman detects only regular, line-of-sight B so this underestimates synchrotron.

Could there be larger random B, maybe also on larger scales? Synchrotron could detect it.

Formulae for reference.

A0.1 Synchrotron emissivity

$$\epsilon_{408} = 4.34\ 10^{-40} (B_{rand}/10\ \mu G)^{(\gamma+1)/2}\ erg\ cm^{-3}\ sr^{-1}\ s^{-1}\ Hz^{-1}$$

$$= 0.026\ (B_{rand}/10\ \mu G)^{(\gamma+1)/2}\ K\ pc^{-1}$$

A0.2 Given line-of-sight

$B = B_o (n / n_o)^{\kappa}$

For line-of-sight L,

$$T_{408} = 261\ (B_{rand}/10\ \mu G)^{(\gamma+1)/2}\ (L/10\ kpc)\ K$$

$$T_{408} = 2.81\ 10^{-23} N_H (B_0/10)^{(\gamma+1)/2} (300/n_0)(n/n_0)^{\kappa(\gamma+1)/2\ -1}\ \mathrm{K}$$

A0.3 Single cloud

Consider a spherical cloud of radius r and distance d, random B-field B_{rand}.

The flux at 408 MHz is

$$S_{408} = 0.52\ (B_{rand}/10\ \mu G)^{(\gamma+1)/2}\ (r/10\ pc)^3\ (d/1000\ pc)^{-2}\ Jy$$

where $\gamma = 3.14$ is the electron spectral index. For a measured B_{rand}, or using $B(n)$, the flux can then be computed.

Based on full synchrotron calculation using cosmic-ray electron + positron spectrum.
(software available at *https://sourceforge.net/projects/galpropsynchrotron*)

Estimated synchrotron emission from some clouds

Table 1: Molecular cloud data from [10] with estimates of predicted synchrotron flux density (mJy) at 1 GHz based on the statistical B–n_{H} scaling law.

Name	$\|B\|$ [μG]	$n_{\mathrm{H_2}}$ [cm^{-3}]	R [pc]	D [kpc]	θ [arcmin]	T_{GHz} [mK]	$S_{\mathrm{GHz}}^{\mathrm{pred}}$ [mJy]
W3 OH	3100	6.31e+06	0.02	2.0	0.03	0.024	0.125
DR21 OH	710	2.00e+06	0.05	1.8	0.09	0.092	0.489
Sgr B2	480	2.51e+03	22.00	7.9	9.57	46.0	244.4
M17 SW	450	3.16e+04	1.00	1.8	1.96	2.6	13.7
W3 (main)	400	3.16e+05	0.12	2.0	0.20	0.084	0.447
S106	400	2.00e+05	0.07	0.6	0.40	0.11	0.586
DR21 OH2	360	1.00e+06	0.05	1.8	0.09	0.035	0.187
OMC-1	360	7.94e+05	0.05	0.4	0.42	0.52	2.7
NGC2024	87	1.00e+05	0.20	0.4	1.64	1.8	9.4
W40	14	5.01e+02	5.00	0.6	28.65	8.8	46.7
ρ Oph 1	10	1.58e+03	0.03	0.1	0.76	0.0049	0.026

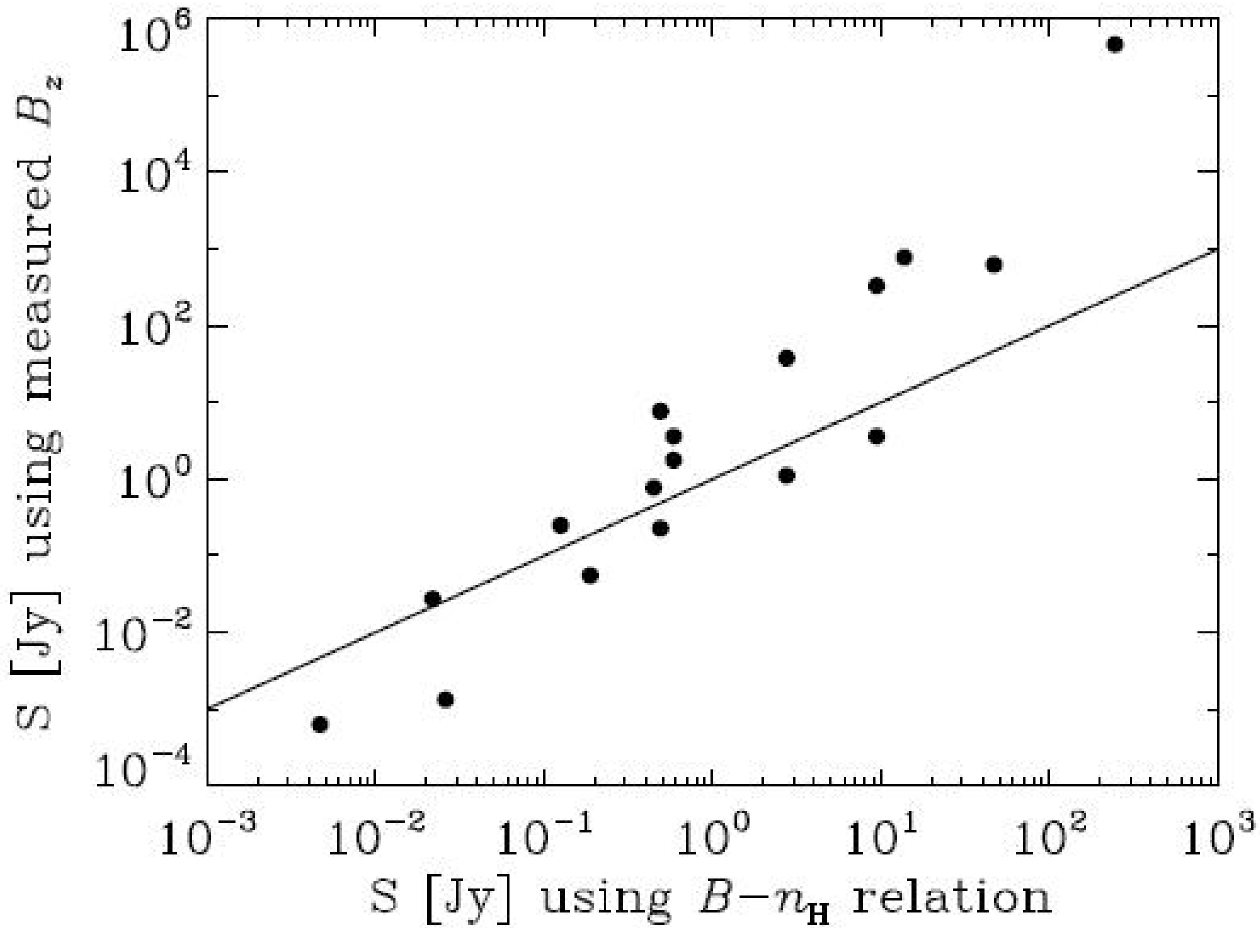


Figure 2. Comparison of predicted flux densities, S, from the measured B_z values (Crutcher 1999) and the from using the empirical B_z–n_H relation. The solid line is the 1:1 line.

Regular **B** does not increase if collapse along **B**
→ reason for regular **B** = constant for $n < 300\ cm^{-3}$

However....

Random **B** should always increase with compression
→ random **B** should increase from interstellar $n = 1\ cm^{-3}$ upwards

If this is the case, synchrotron could detect it.

Synchrotron as potential probe of B in clouds:

Single dish telecopes: generally not sensitive enough.

JVLA: worth trying

Need: low frequency (to avoid free-free emission)
multi-frequency (for component separation)
polarization (signature of synchrotron)
high resolution (since B concentrated in dense cores)

→ SKA: should be possible.
SKA-MID:
Sub-mJy, arcsec sources, frequencies down to 350 MHz: OK
Input to SKA Proposal Book.

Complementary to Zeeman,
Detects *total* ***B*** not just regular or line-of-sight.

Complementary to optical polarization, CF method : less assumptions required

On large scales, observed correlation of synchrotron with CO is a hint of global clould emission.
This will also benefit from new large-scale continuum surveys and high-resolution observations of exernal galaxies.

for more details :
Strong, Dickinson etal. in preparation

END

ADDITIONAL MATIERAL

Estimated synchrotron emission from some clouds

Table A1. Molecular cloud data from Crutcher (1999) with predicted synchrotron flux density (mJy) at 408 MHz. The observed flux density limit has been scaled to 408 MHz assuming a spectral index $\alpha = -0.8$. Magnetic field strengths from [a]Crutcher (1999) and [b]Poidevin et al. (2013). $S_{408}^{\rm pred1}$: flux using B(n) relation, $S_{408}^{\rm pred2}$: flux using measured B.

Name	$\|B\|$ [μG]	n_{H_2} [cm^{-3}]	R [pc]	D [kpc]	θ [arcsec]	T_{408} [mK]	$S_{408}^{\rm pred1}$ [mJy]	$S_{408}^{\rm pred2}$ [mJy]	$S_{408}^{\rm obs}$ [mJy]	Notes
W3 OH[a]	3100	6.31e+06	0.02	2.0	0.03	0.29	0.256	0.249	$\sim$ 14?	$T_b \approx 8K$ (2.695 GHz) (Furst et al. 1990).
DR21 OH1[a]	710	2.00e+06	0.05	1.8	0.09	1.1	1.0	0.226		Very bright thermal emission
DR21 OH1[b]	3897	2.00e+06	0.05	1.8	0.09	1.1	1.0	7.7		Very bright thermal emission
Sgr B2[a]	480	2.51e+03	22.00	7.9	9.57	565.9	500.7	464245.2		3.2 ± 0.5 Sgr B2 (SC) only (Jones et al. 201
M17 SW[a]	450	3.16e+04	1.00	1.8	1.96	31.8	28.2	777.4		Very bright thermal emission
W3 (main)[a]	400	3.16e+05	0.12	2.0	0.20	1.0	0.915	0.775		Very bright in radio maps incl. SNRs
S106[a]	400	2.00e+05	0.07	0.6	0.40	1.4	1.2	1.8		Very bright thermal emission
S106[b]	562	2.00e+05	0.07	0.6	0.40	1.4	1.2	3.6		Very bright thermal emission
DR21 OH2[a]	360	1.00e+06	0.05	1.8	0.09	0.43	0.384	0.055		Very bright in radio maps
OMC-1[a]	360	7.94e+05	0.05	0.4	0.42	6.4	5.6	1.1	$<\sim$ 12?	Very bright in radio maps
OMC-1[b]	1976	7.94e+05	0.05	0.4	0.42	6.4	5.6	37.9	$<\sim$ 12?	Very bright in radio maps
NGC2024[a]	87	1.00e+05	0.20	0.4	1.64	21.8	19.3	3.6		Very bright in radio maps
NGC2024[b]	773	1.00e+05	0.20	0.4	1.64	21.8	19.3	330.9		Very bright in radio maps
W40[a]	14	5.01e+02	5.00	0.6	28.65	108.1	95.7	627.6	$<\sim$ 1?	Relatively bright in radio maps (off the plan
W40	14	5.01e+02	0.05	0.6	0.29	0.011	0.010	0.001	0.4	Pirogov et al. (2013)
ρ Oph 1[a]	10	1.58e+03	0.03	0.1	0.76	0.060	0.053	0.001		
ρ Oph 1[b]	43	1.00e+03	0.03	0.1	0.76	0.050	0.045	0.027		

Observed fluxes dominated by thermal emission!

$$B = B_o \qquad (n < n_o)$$

$$B = B_o (n / n_o)^{\kappa} \quad (n > n_o)$$

If e.g. compressed from general ISM:

$$\kappa = 0.5$$
$$n_o = 1 \text{ cm}^{-3}$$

Then clouds would shine brightly in synchrotron!

However if $n \sim 100$ cm^{-3}
the effect is much smaller.

Can already deduce $n_o >> 1$ just from non-detection of large-scale correlation with CO!

Independent of Zeeman etc measurements.