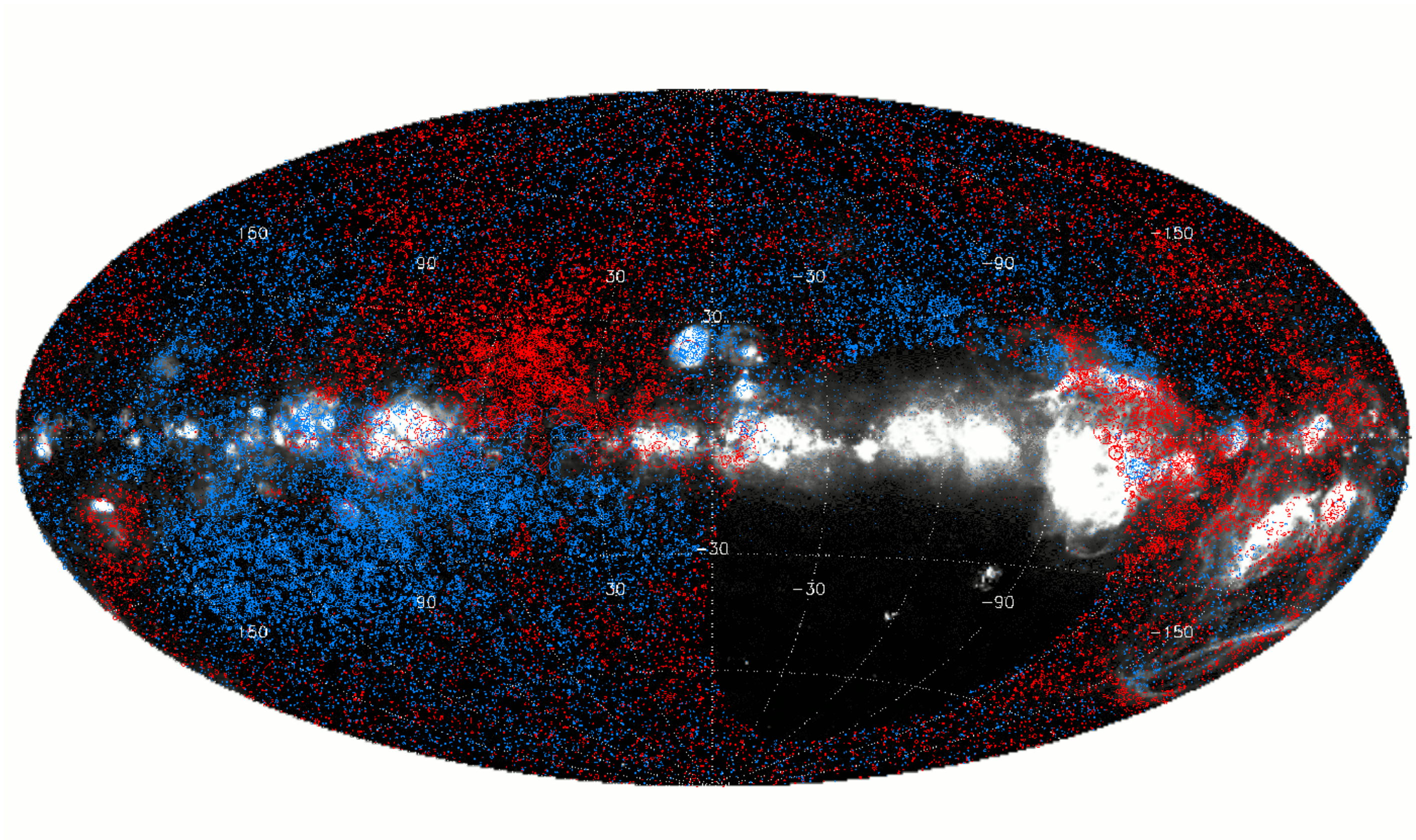
Polarization of the Radio Sky



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Why Polarization?

Radio continuum emission at cm wavelengths is almost always dominated by synchrotron emission which is linearly polarized depending on magnetic field structure.

Thermal free-free emission (unpolarized) is significant but not dominant in galaxies.

Faraday rotation of the plane of polarization as a linearly polarized wave travels through a magnetized plasma.

Median percentage polarization for extragalactic sources is ~ 2%. Polarization purity well below 1% is quite valuable.

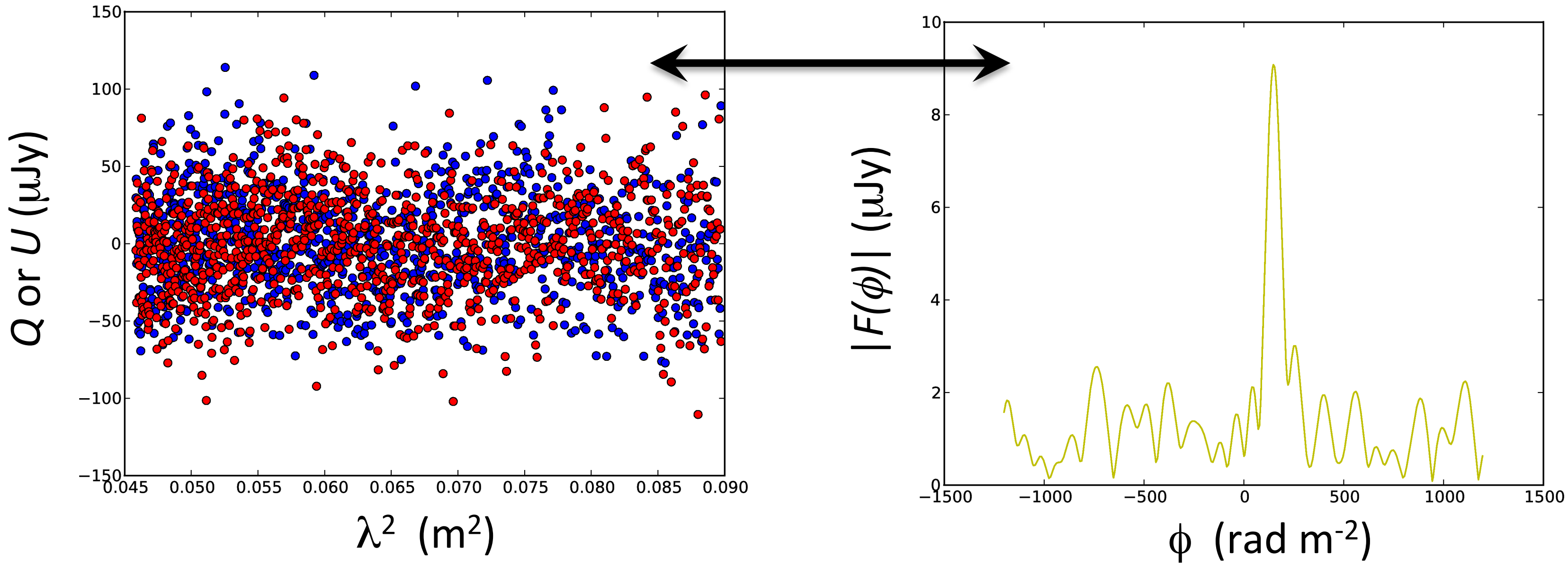
Circular polarization not considered here.

Rotation Measure Synthesis

$$Q(\lambda^2) + iU(\lambda^2) = \int_{-\infty}^{+\infty} F(\phi) e^{2i\phi\lambda^2} d\phi$$

$$\phi = 0.81 \int_{\mathrm{l.o.s.}} n_e B_{\|} dl$$

Burn (1966)
Brentjens & De Bruyn (2006)



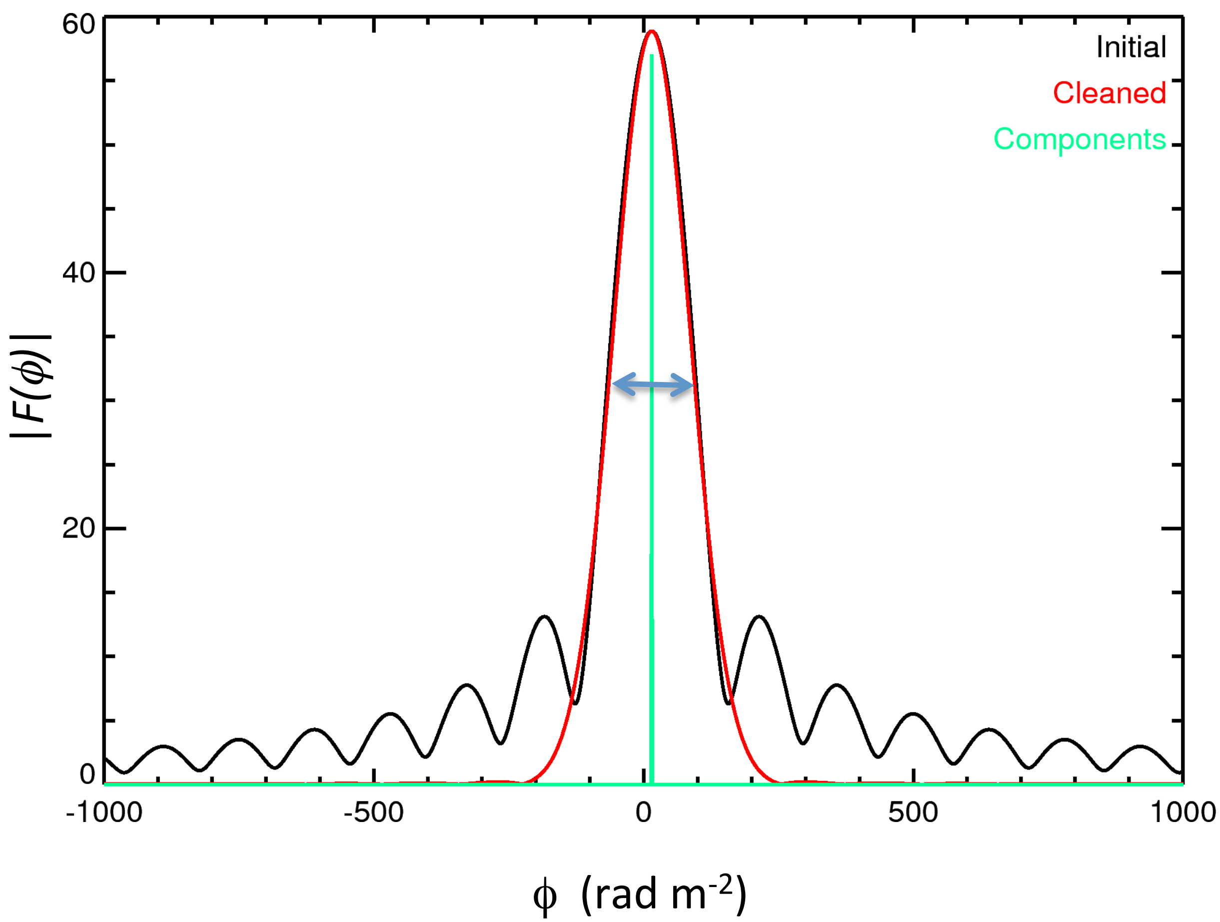
Source parameter **<u>fitting</u>**?

Source **<u>detection</u>**!

See RM Synthesis Challenge (Sun et al. in prep.), Round 2 in 2014

<u>We need to divide out the Stokes I spectral dependence</u>

RM Synthesis and Frequency Range

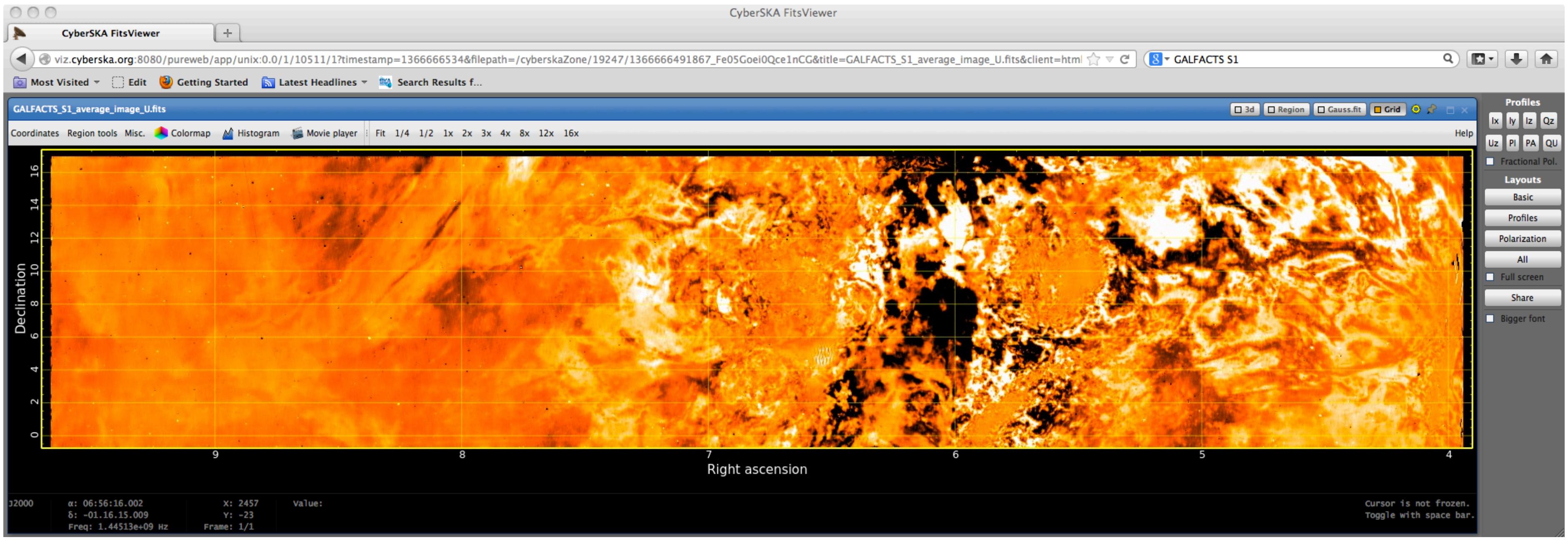


Better resolution in Faraday depth is an argument for lower frequency observations (~300 MHz to 2 GHz)

Depolarization and sensitivity to extended structure in ϕ are arguments for higher-frequency observations (2 - 4 GHz)

See Brentjens & De Bruyn (2006) for details

Galactic Foreground



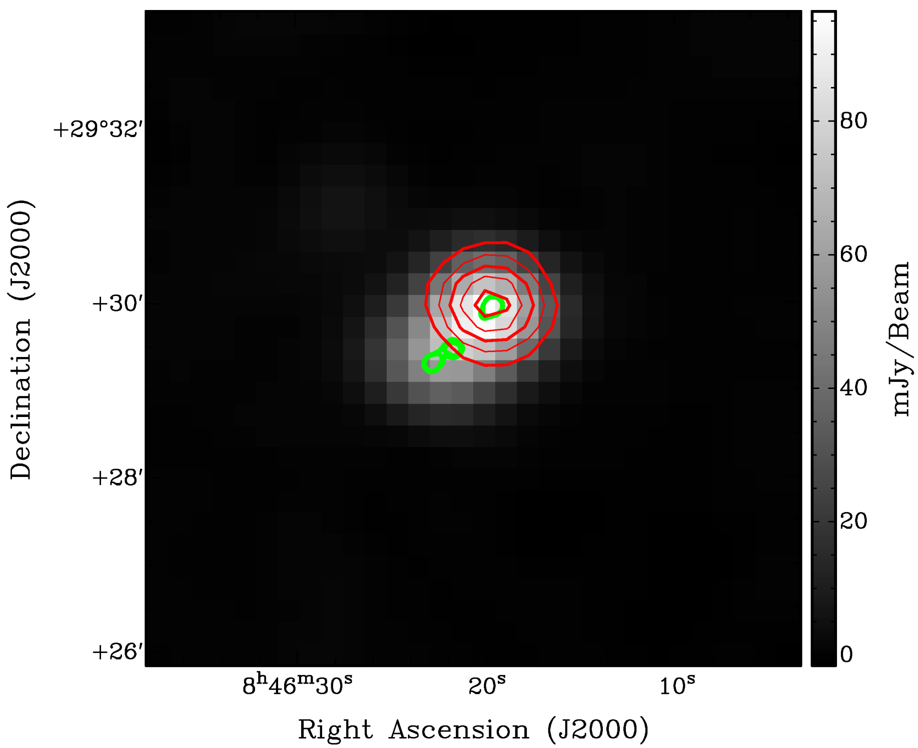
GALFACTS S1 region, Stokes U, 3' resolution with Arecibo

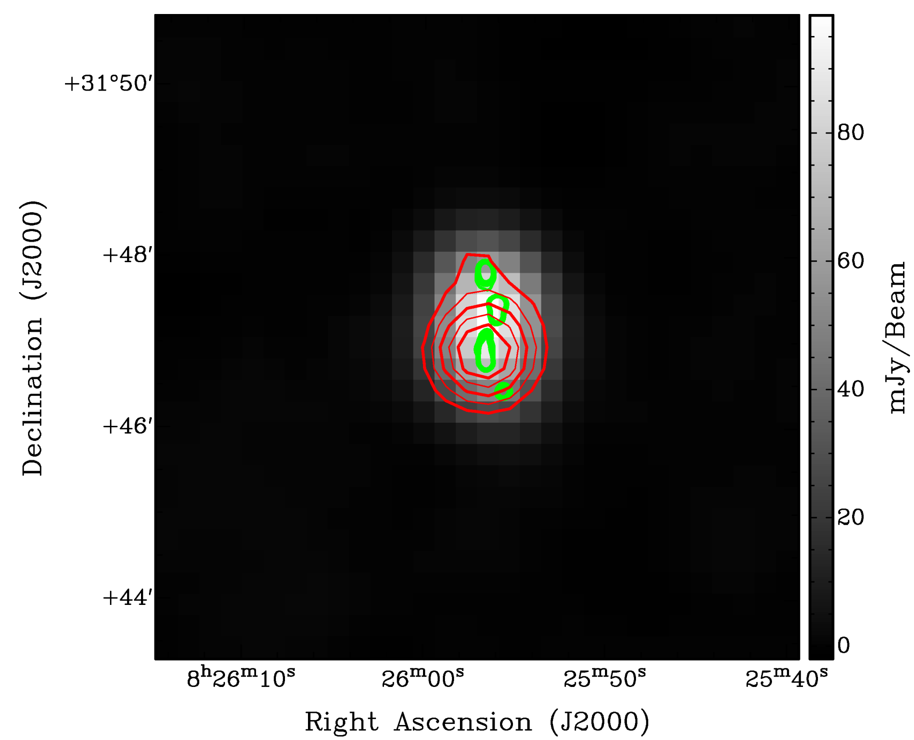
Small-scale structure in polarization angle visible in NVSS Stokes Q and U images, sometimes far from the Galactic plane (Rudnick & Brown 2009).

Zero-spacing data would need the same frequency coverage as VLA survey.

Extragalactic Sources
A Case for Source Finding in P

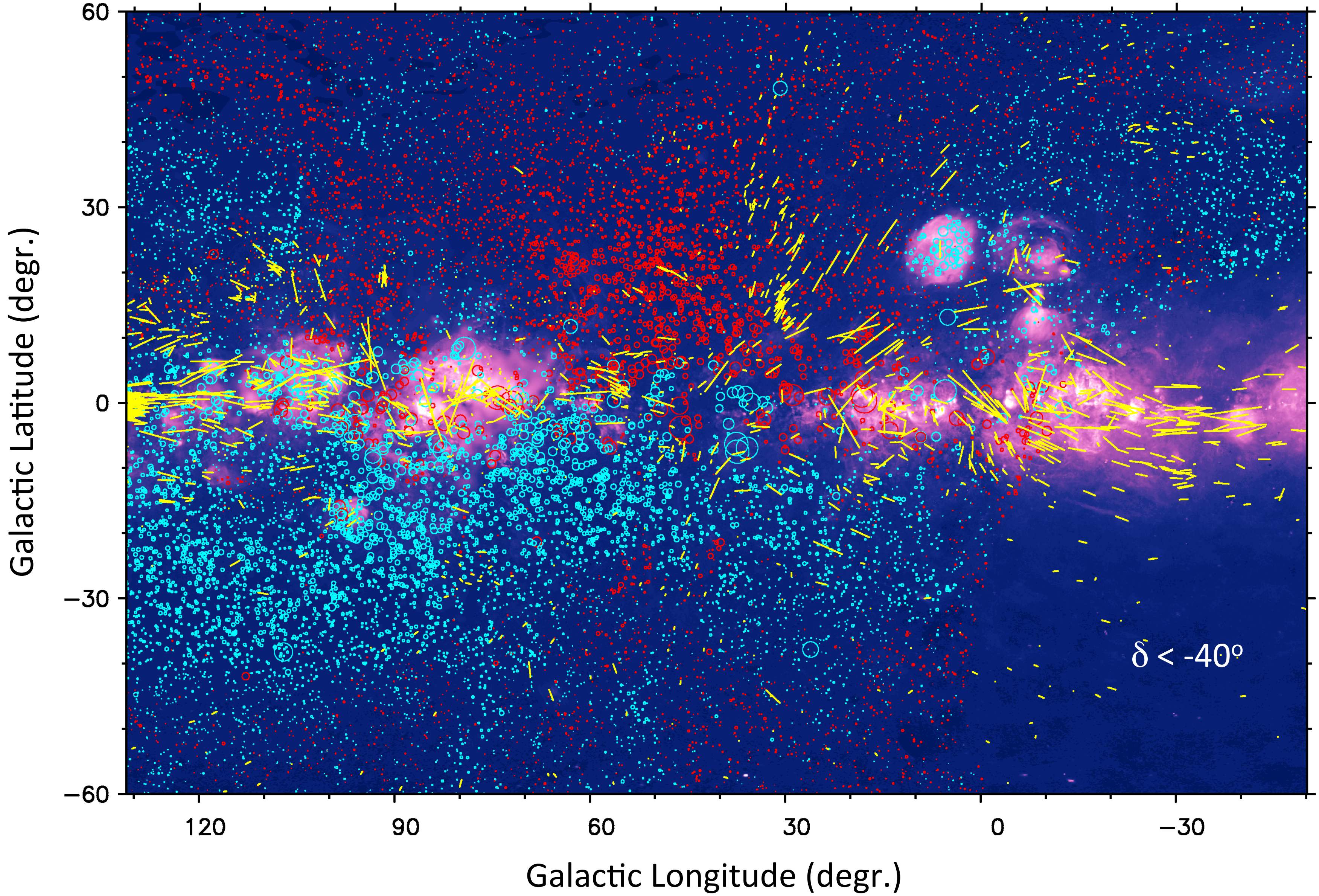
Blending of polarized components is a driver for arcsec resolution.
Some evidence that higher degree of polarization is associated with extended emission (e.g. Grant et al. 2010). Also need sensitivity on angular scales of tens of arcsec.



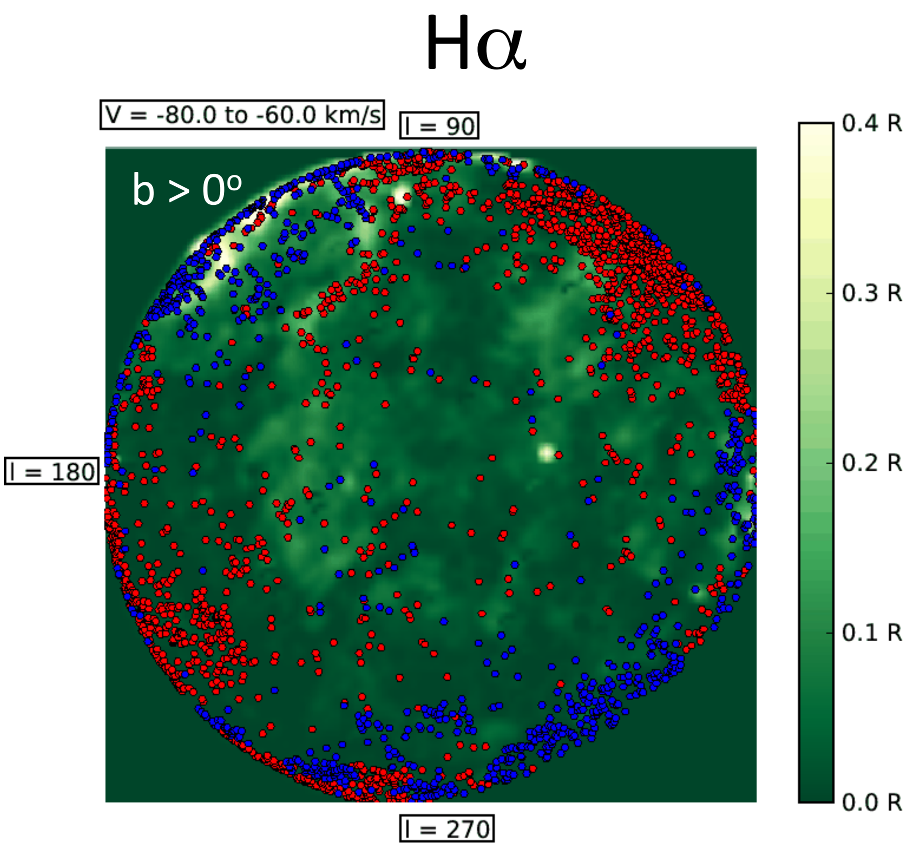


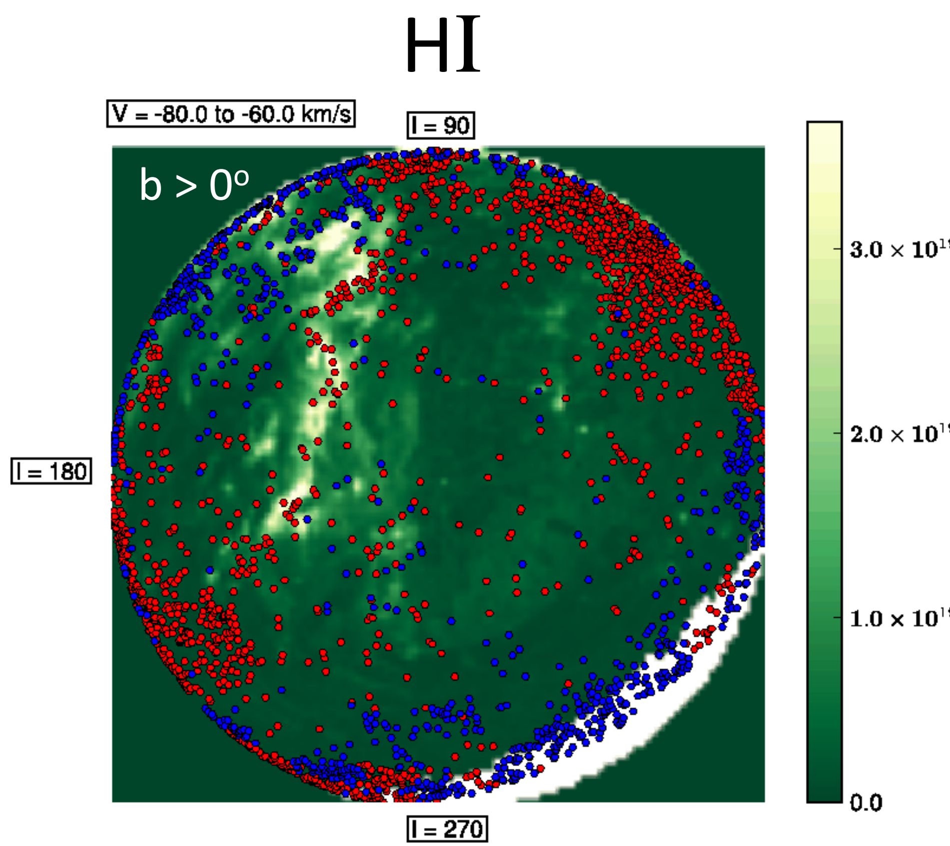
Gray scale: NVSS Stokes I. Red contours: NVSS polarized intensity.
Green contours: FIRST Stokes I

Faraday Rotation is Sensitive to Otherwise Unobservable Plasma. There is Structure Nearly Everywhere



High-latitude RM structure





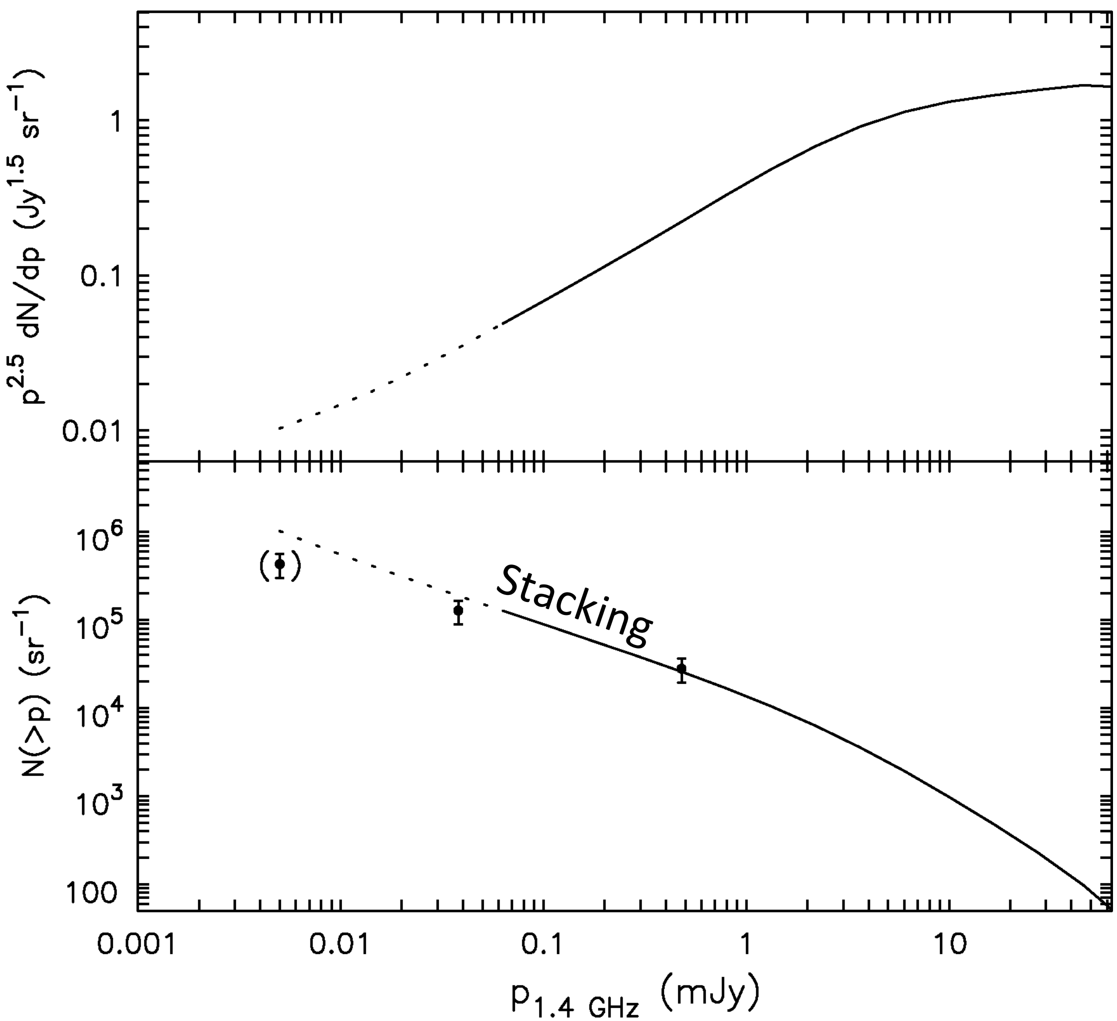
Censored RM catalogue on to op Hα (WHAM survey; left) and HI (LD survey; right)

Red: RM > +30 rad m^{-2} and Δ RM < 10 rad m^{-2}

Blue: RM < -30 rad m^{-2} and Δ RM < 10 rad m^{-2}

Significant structure at high latitudes in North and South

Expected Number of Polarized Sources



Polarized intensity at 1.4 GHz

Curve: stacking NVSS polarized intensity at 60” resolution from Stil et al. ApJ submitted. Dotted: extrapolation.

Symbols: GOODS-N at 1.6” resolution from Rudnick & Owen ApJ submitted. Bracketed: extrapolation.

N(p>5 μJy) = 3×10^5 to 1×10^6 sr^{-1}

A Stacking Analysis of the Free-Free Opacity of Spiral Galaxy Disks

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Free-Free absorption in spiral galaxies below 100 MHz occurs in relatively dense plasma that also completely depolarizes background synchrotron emission at GHz frequencies. The free-free opacity of galaxies as a function of inclination therefore allows us to determine the amount of depolarization by HII regions in models of polarized synchrotron emission of galaxies. We present a stacking analysis of radio emission of spiral galaxies, using the NRAO VLA Sky Survey (NVSS at 1400 MHz), the Westerbork Northern Sky Survey (WENSS at 325 MHz) and the VLA Low-frequency Sky Survey (VLSS at 74 MHz). Using median flux densities, we derive spectral indices $\alpha^{1400}{}_{325} = -0.86 \pm 0.03$ and $\alpha^{325}{}_{74} = -0.60 \pm 0.10$. We do not find a significant dependence of the low-frequency spectral index on inclination, but we do find that edge-on galaxies in our optically selected sample are fainter at all three radio frequencies, as well as extinction-corrected near-infrared K magnitude. We interpret this as an inclination-dependent selection effect in the input catalog that favors low surface brightness galaxies in the edge-on sample.

Free-Free Opacity of Spiral Galaxies

The free-free opacity of a plasma with electron density n_e, temperature T_e, and depth l along the line of sight is (e.g. Condon 1992)

$$\tau_\nu = 0.206\left(\frac{T_e}{10^4\ \mathrm{K}}\right)^{-1.35}\left(\frac{\nu}{100\mathrm{MHz}}\right)^{-2.1}\left(\frac{n_e}{10\ \mathrm{cm}^{-3}}\right)^2\left(\frac{l}{50\ \mathrm{pc}}\right)$$

Significant free-free absorption occurs at low frequencies in HII regions with a small filling factor. Such HII regions also depolarize Galactic synchrotron emission at 1.4 GHz (e.g. Gaensler et al. 2001, Landecker et al. 2010). We investigate free-free absorption as a proxy for the covering factor of synchrotron emission by relatively dense plasma in spiral galaxies. Israel & Mahoney (1990) claimed a relation between low-frequency spectral slope and inclination for 68 late-type galaxies and attributed this to free-free absorption. Hummel (1991) disputed the trend with inclination, suggesting that there is no evidence to support free-free absorption over intrinsic spectral steepening at higher frequencies. However, the sample size (27) appears too small to rule out an inclination effect for only the most edge-on galaxies, and the scatter in spectral slopes is larger than the measurement errors, suggesting that a significant improvement in *sample size* is required to detect a smaller inclination effect with statistical significance.

Here we report results from a stacking analysis of radio emission from spiral galaxies of type Sb to Scd at 1.4 GHz (NVSS, convolved to 1' resolution; Condon et al. 1998), 325 MHz (WENSS; Rengelink et al. 1997), and 74 MHz (VLSS; Cohen et al. 2007). We selected spiral galaxies from the Principal Galaxy Catalog (PGC; Paturel et al. 2003) with major axis between 0.6' and 1.1' and subdivided these by optical axial ratio into four subsamples. **Figure 1** shows the stacked images as contours on DSS images of representative galaxies in each subsample. To optimize sensitivity we did not require the samples to be covered by *every* survey (WENSS is significantly smaller than NVSS and VLSS). Flux densities were corrected for the finite extent of the galaxies in the beam by calculating the fraction of the flux density recovered for a uniform disk at the median axial ratio and size for each subsample.

Figure 2 shows flux densities and spectral indices as a function of major-to-minor axial ratio R_{25}. We find a relation with inclination, with the most edge-on galaxies significantly fainter at *every* frequency. The spectral index does not rise significantly with inclination, with the errors dominated by the sensitivity of the 74 MHz images. Stacking the combined low-inclination subsample ($R_{25} < 2.5$), we obtain $\alpha^{1400}{}_{325} = -0.86 \pm 0.03$ and $\alpha^{325}{}_{74} = -0.60 \pm 0.10$. Hummel (1991) found $\alpha_{high} = -0.76$ and $\alpha_{low} = -0.57$, using data at somewhat different frequencies. Our high-frequency spectral index is marginally steeper, but the magnitude of the spectral break as measured by $\alpha_{low} - \alpha_{high}$ is consistent with Hummel's value 0.25.

Why are edge-on galaxies fainter in our sample?

We have investigated various potential systematic differences between the samples. Isophotal diameters of edge-on galaxies are larger than those of similar face-on galaxies (e.g. Paturel 1975). **Figure 3** shows distributions of redshift and near-IR K band magnitude from 2MASS for the edge-on subsample ($R_{25} > 2.5$; yellow) compared with the combined subsamples $R_{25} < 2.5$ (black). The redshift distributions of the subsamples are not significantly different, but the edge-on subsample is about 0.3 mag fainter in K-band. The extinction correction for the edge-on sample is only ~ 0.1 mag (Tully et al. 1998). In terms of distance modulus, 0.3 mag would amount to 15% higher redshift for the edge-on galaxies (40% to explain the lower radio flux density), which is inconsistent with the observed redshift distributions.

We interpret the lower IR fluxes in the edge-on sample as a selection effect in the input catalog that favors galaxies with lower surface brightness if they are seen edge-on. These galaxies are expected to have a lower star formation rate, and therefore a lower ratio of radio to optical/near-IR flux density. We do find a sharper drop in radio flux density than in near-IR flux density, indicating a higher value of the ratio L_{radio}/L_K.

Conclusions

Our stacking experiment does not show a significant inclination dependence of the low-frequency spectral index. This confirms the result of Hummel et al. (1991) at a similar significance level, but for a much larger sample. A complication for the interpretation of the stacking analysis is that our sample of edge-on galaxies was found to include more galaxies that are intrinsically faint in the radio and near-infrared. These galaxies may have different star formation rates and magnetic field properties that would affect the emitted synchrotron spectrum and free-free absorption. Careful sample selection that ensures a homogeneous sample as a function of inclination is required for future experiments.

The sensitivity of our experiment is limited by the sensitivity of the VLSS survey. Future surveys below 100 MHz, for example with LOFAR, will have the sensitivity to reduce the statistical errors in the low-frequency spectral index to less than 0.05, where we may detect a dependence on inclination.

References

Cohen, A. S., Lane, W. M., Cotton, W. D. et al. 2007, AJ 135, 1245
Condon, J. J., Cotton, W. D., Greisen, E. W. et al. 1998, AJ 115, 1693
Condon, J. J. 1992, ARAA, 30, 575
Gaensler, B. M., Dickey, J. M., McClure-Griffiths, N. M. et al. 2001, ApJ, 549, 959
Hummel, E. 1991, A&A, 251, 442
Israel, F. P., & Mahoney, M. J. 1990, ApJ, 352, 30
Landecker, T. L., Reich, W., Reid, R. I. et al. 2010, A&A 520, A80
Paturel, G., Petit, C., Prugniel, Ph. et al. 2003, A&A 412, 45
Paturel, G. 1975, A&A 40, 133
Rengelink, R. B., Tang, Y., De Bruyn, A. G. et al. 1997, A&AS 124, 259
Tully, R. B., Pierce, M. J. Huang, J.-S. et al. 1998, AJ, 115, 2264

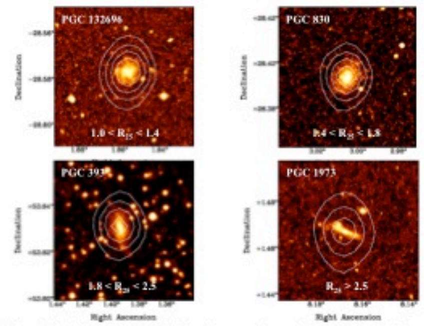

Figure 1 Stacked 1.4 GHz total intensity shown as contours on images of representative galaxies in the input catalogs. The subsamples were selected by optical major axis to minor axis ratio R_{25} as indicated. Contour levels are 0.4, 0.6, 0.8, and 1.0 mJy/beam, except for the bottom-right panel that has contours at 0.2, 0.4, and 0.4 mJy/beam. Flux densities and spectral indices have been corrected for the finite size of the galaxies in the beam, depending on optical axial ratio.

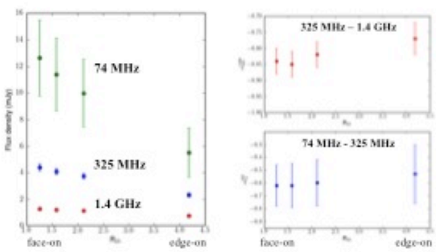

Figure 2 *Left: Flux density as a function of apparent optical axial ratio R_{25} (major axis to minor axis size). The noise in the surveys is: 0.45 mJy/beam (NVSS), 3.6 mJy/beam (WENSS), and 100 mJy/beam (VLSS). Flux densities have been corrected for the finite extent of the galaxy in the synthesized beam. The flux density is significantly lower for edge-on galaxies at every frequency. Right: Spectral index as a function of optical axial ratio. A subtle, not statistically significant, flattening of the spectrum is seen in both spectral indices, suggesting an error less than ~0.05 in the low-frequency is required.*

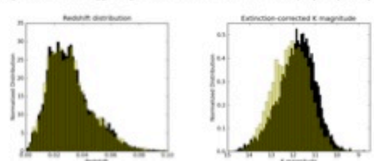

Figure 3 *Distributions of redshift (left) and extinction-corrected K magnitude from 2MASS (right) for subsamples with optical axial ratio $R_{25} < 2.5$ (black) and $R_{25} > 2.5$ (yellow). The edge-on sample is 0.3 mag fainter. Interpreted as a difference in distance modulus, this would amount to a 15% larger distance, which is excluded by the similarity of the redshift distributions.*

Acknowledgements

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Consider stacking a real application of any survey

Information may be lost when publishing only band-averaged images

Poster presented on Thursday at this meeting

Conclusions

- Surveys of linear polarization reveal magnetic field structure in extragalactic sources and the Milky Way.
- The Galactic foreground is nearly everywhere.
- Polarization data products: images and a much more complicated source catalog
- Polarization is a driver for higher bandwidth, and a large range of angular scales.