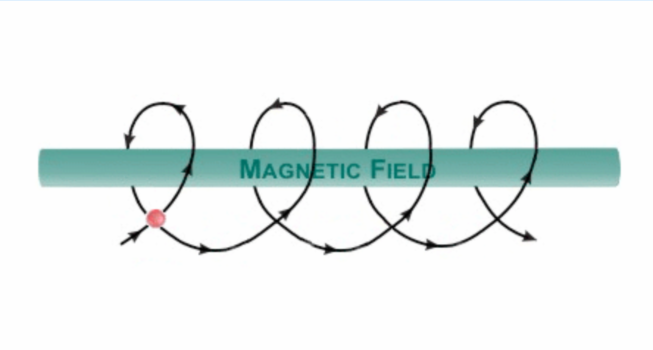
Magnetized ISM in M33

Fatemeh Tabatabaei

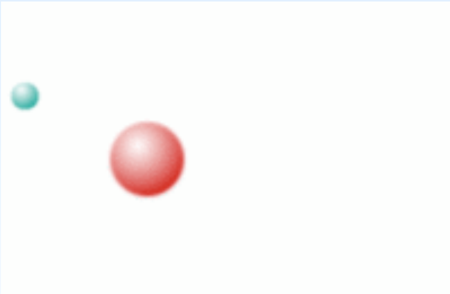
Radio Continuum Components

Nonthermal (synchrotron) emission



- from the SNRs and diffuse ionized gas
- strong linear polarization
- with a steep power-law spectrum
- study of magnetic field: strength and orientation
- cosmic-ray electrons and their distribution

Thermal (free-free) emission



- from HII regions and diffuse ionized gas
- not polarized
- flat spectrum

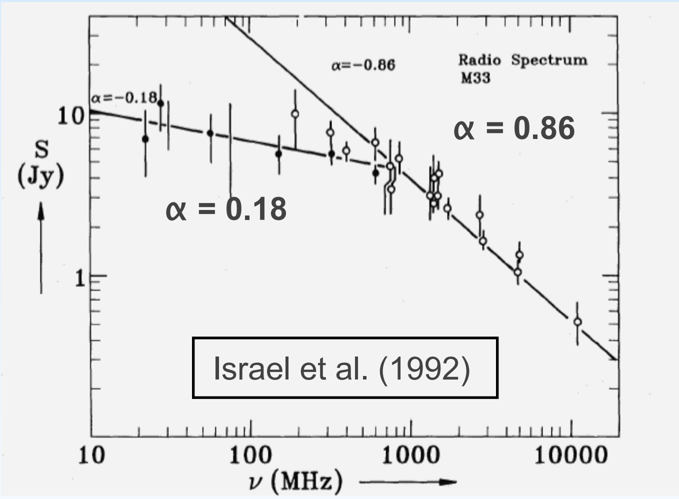
Overview on Radio Continuum

- Terzian & Pankonin (1972): some diffuse emission at 318 and 606 MHz (θ>10′)
- Von Kap-Herr et al. (1978): first detection of diffuse spiral arms at 5 GHz
- Beck (1979): first detection of polarized emission at 1.4 GHz
- Buczilowski & beck (1987, 1991): 5 GHz polarization from northern M33, bisymmetric B
- Viallefond et al. (1986), Duric et al. (1993), Gordon et al. (1999):

  higher resolution and sensitivity interferometer observations in total intensity

  -> surveys of HII regions & SNRs (~110 SNR of 2338)
- Israel et al. (1992): Spectral flattening for ν< 800 GHz

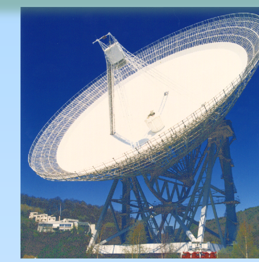
  -> Thermal absorption of RC?



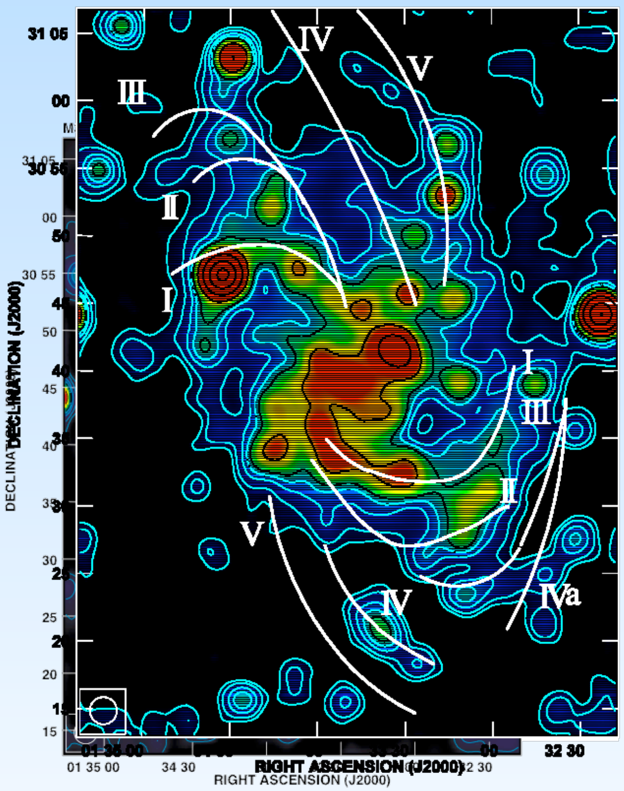
M33 relatively weak in radio:
e.g. at 5 GHz,
S(I) ≈ 1300 mJy , S(PI) ≈ 89 mJy

Buczlowski (1987), Tabatabaei (2007)

λ3.6cm Radio Continuum

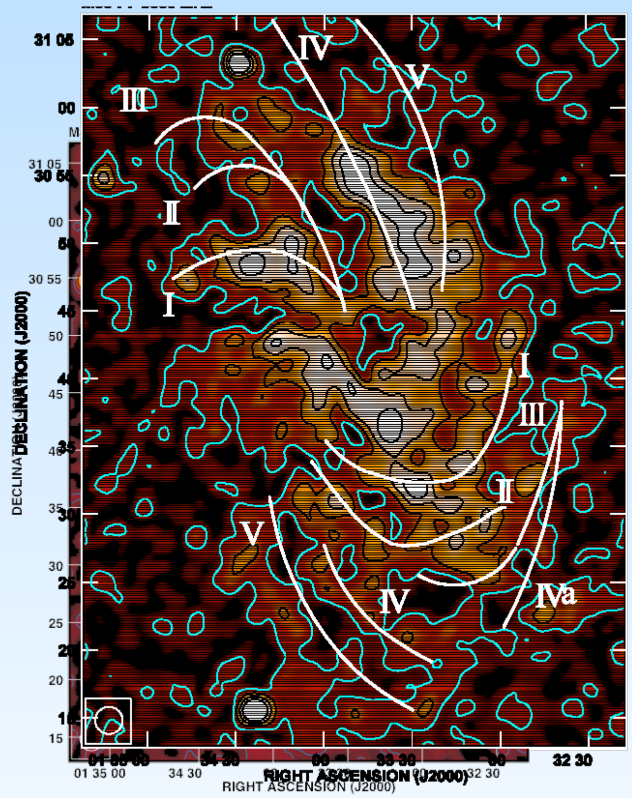


Total intensity (TI)



HPBW = 84″
Noise level ~ 220μJy/beam

Polarized intensity (PI)

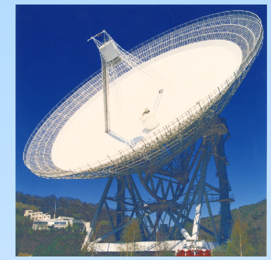


Noise level ~ 40 μJy/beam

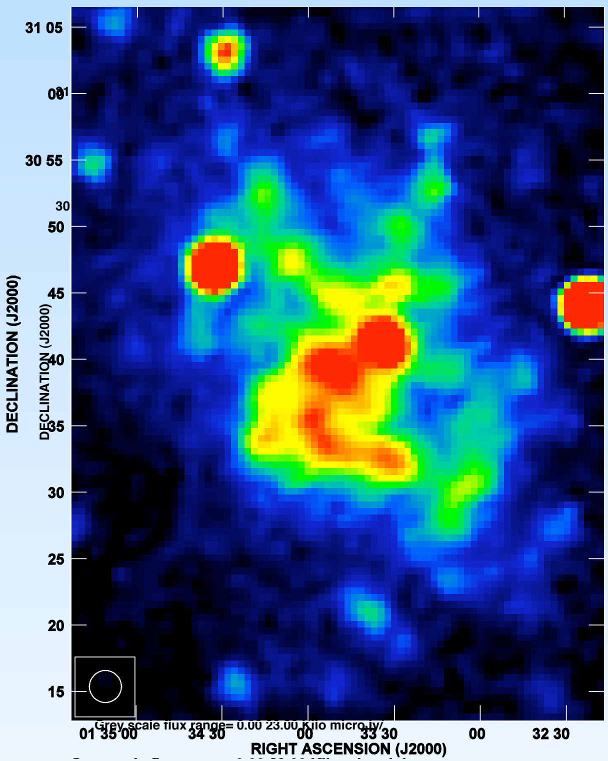
- Detection of high-frequency radio emission not only from IS and IN but also from weaker arms
- PI follows a spiral structure
- Strongest linearly polarized emission from a filament in north-west of M33

Tabatabaei et al. 2007

λ6.2cm Radio Continuum

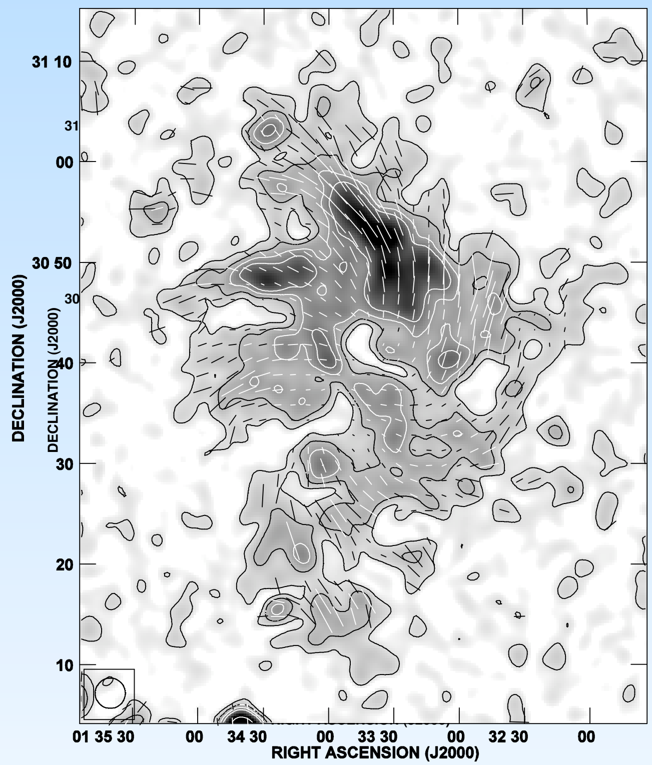


Total intensity (TI)



HPBW =147”
Noise level ~ 700 μJy/beam

Polarized intensity (PI)

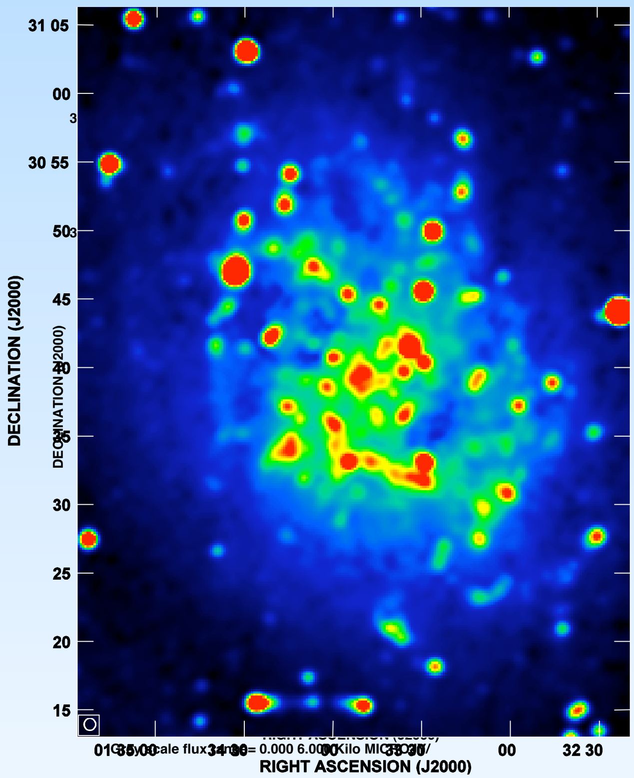


HPBW = 180”
Noise level ~ 120 μJy/beam

contours: PI
vectors : PI/I

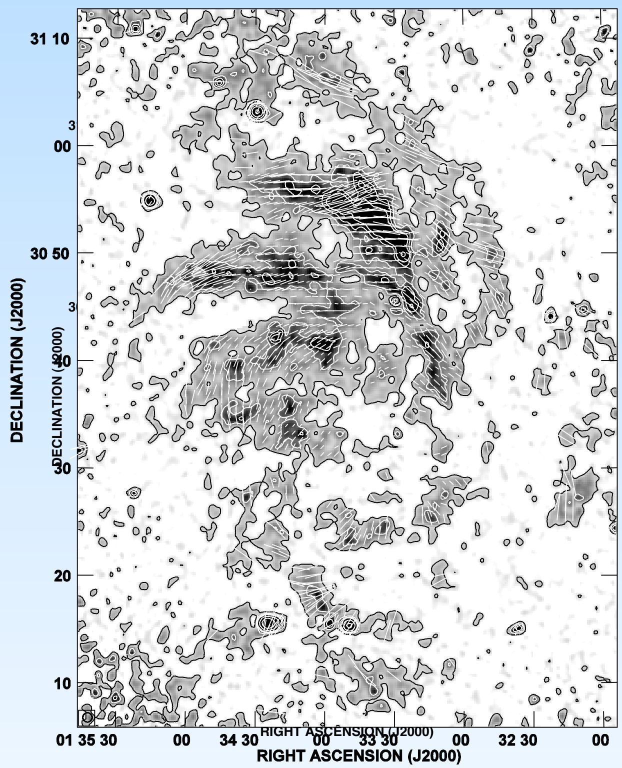
λ21cm Radio Continuum

Total intensity (TI)



HPBW = 51”
Noise level ~ 70 μJy/beam

Polarized intensity (PI)



HPBW = 51”
Noise level ~ 15 μJy/beam

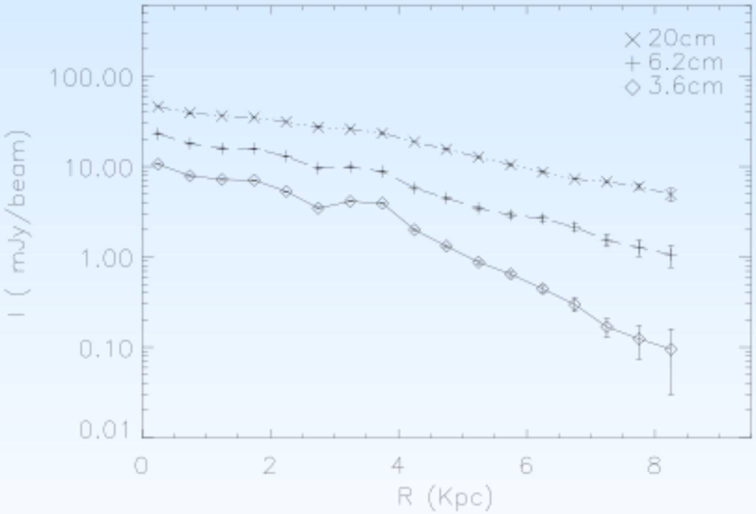
- At 20cm, the VLA integrated total flux is only 15% in total intensity and 55% in polarized intensity of those from single-dish data
- Strong Faraday depolarization in the south

Radio Continuum (Outcomes)

HPBW = 180"   R<8.5kpc

λ (cm)	S (intensity) (mJy)	S (polarized intensity) (mJy)	Degree of polarization (P) %	P(north) / P(south)
3.6	779 ± 66	40 ± 4	5.1 ± 0.7	0.9 ± 0.1
6.2	1284 ± 135	89 ± 4	6.9 ± 0.8	1.5 ± 0.2
20	2768 ± 63	123 ± 3	4.4 ± 0.1	2.2 ± 0.4

Radial profile of total intensity



- Thermal fraction decreases rapidly beyond R=4 kpc
- For both thermal and nonthermal emission: L(R< 4kpc) larger than L(R>4pkc):a spatial coupling between nonthermal emission and SF regions
- Wavelength dependent north-south asymmetry in polarization
- Spectral index of ~ 0.7

Further Studies…

- Magnetic field: strength and structure
- Cosmic ray electron propagation
- Radio – IR correlation

Synchrotron Spectral index

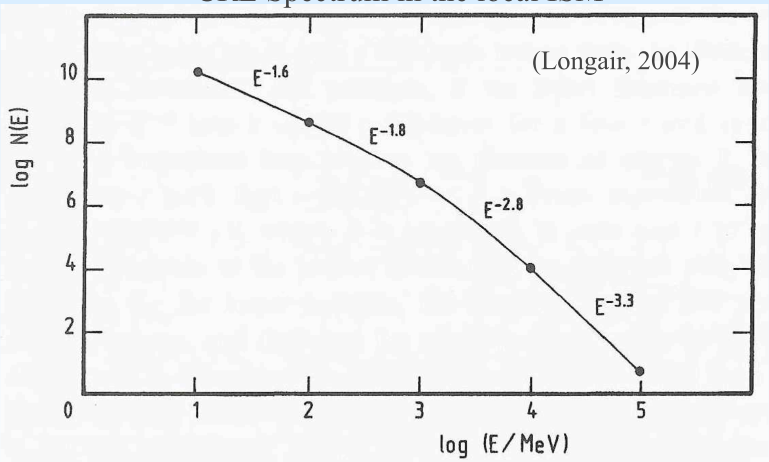
Do the cosmic ray electrons propagate with the same energy index across a galaxy?

$$dN(E) = K\, E^{-\gamma}\, dE$$

$$I(\nu) \propto \nu^{-\alpha_n}, \quad \alpha_n = \frac{\gamma - 1}{2}$$

- their energy spectrum…
- if ionization losses dominate $\longrightarrow$ $N(E) \propto E^{-(\gamma-1)}$
- if Bremsstrahlung or adiabatic losses dominate $\longrightarrow$ $N(E) \propto E^{-\gamma}$
- if inverse Compton or synchrotron losses dominate $\longrightarrow$ $N(E) \propto E^{-(\gamma+1)}$
- time-evolution i.e. evolution with distance from their origin

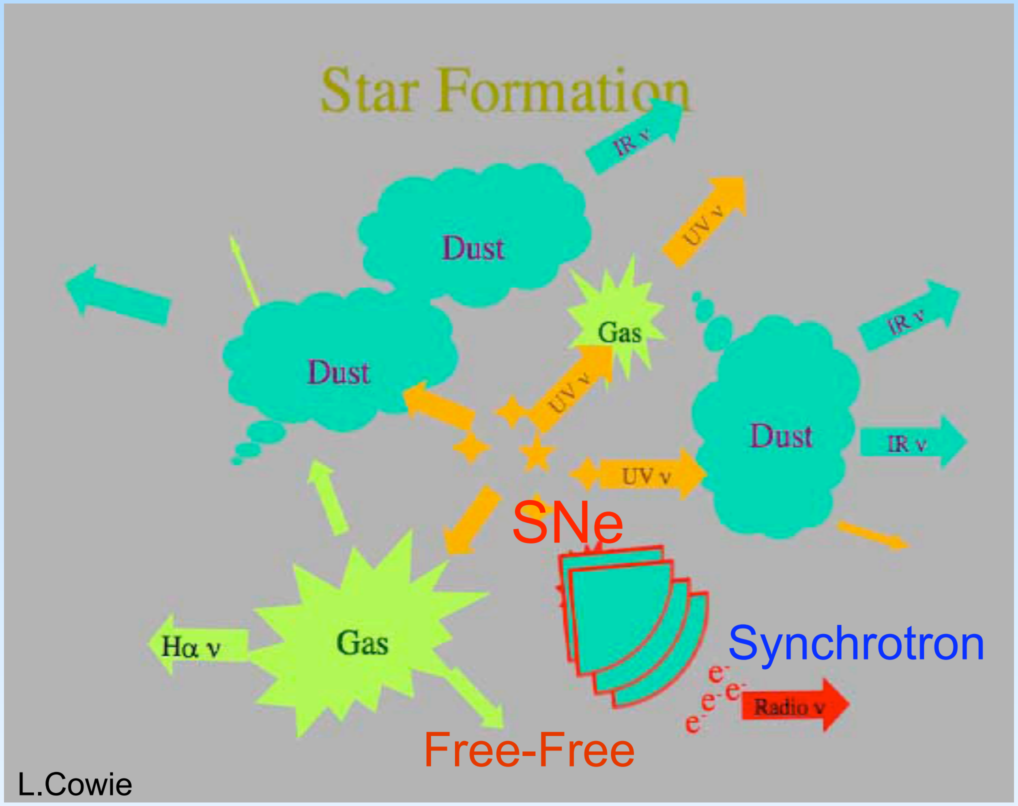
CRE Spectrum in the local ISM



Different phases of the CRE propagation in ISM provide different indices across a galaxy.

Radio – IR Correlation

The radio-IR correlation is explained as the dependence of both radio and IR on massive star formation
(e.g. Helou et al. 1985, Condon 1992, Niklas & Beck 1997)



Uncertainties:

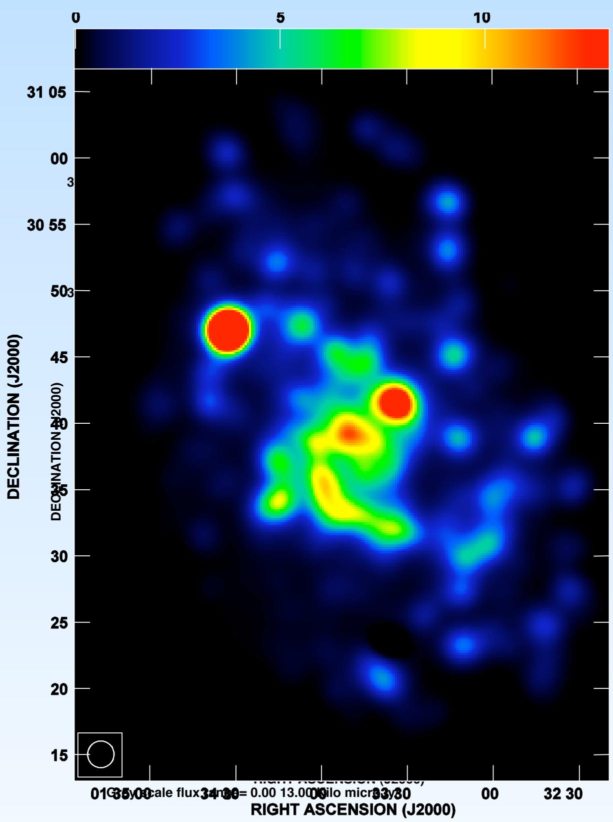
- Connection of cold dust to massive SF?
- Connection of synchrotron to dust (warm/cold)?
- Effects of cosmic-ray propagation?
- Smallest scale at which this correlation holds?

Required:

- Radio thermal/nonthermal separation
- Structural characteristics of FIR and radio emission

Thermal and Nonthermal Emission (λ20 cm)

Thermal emission

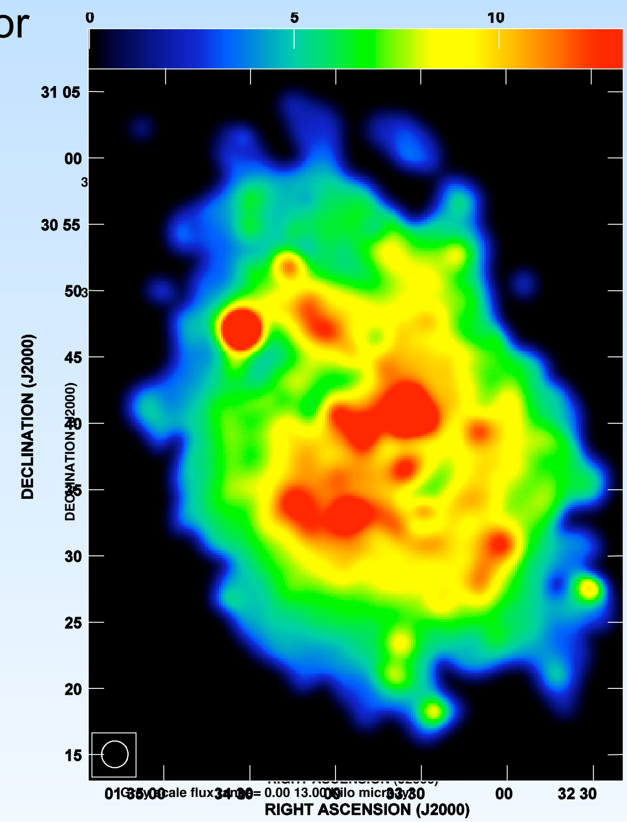


Separation based on thermal template:

Hα emission corrected for extinction by means of Spitzer MIPS data (Tabatabaei et al. 2007)

λ20 cm

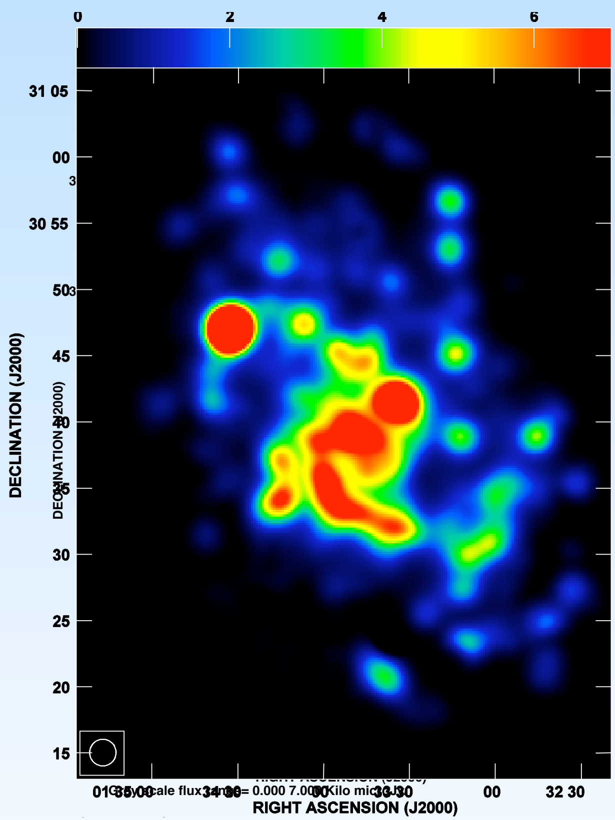
Nonthermal emission



Total thermal fraction = 17.6 % ± 3.1%

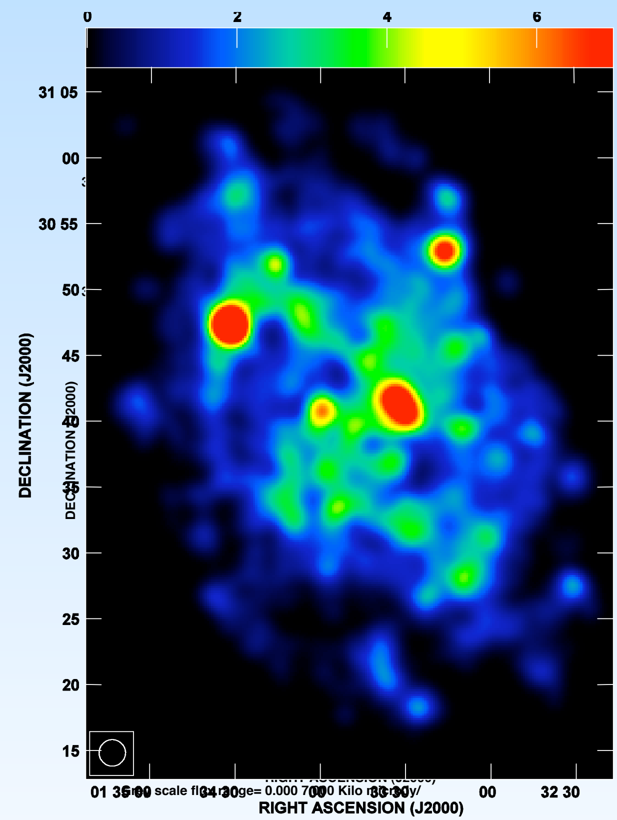
Thermal and Nonthermal Emission (λ3.6 cm)

Thermal emission



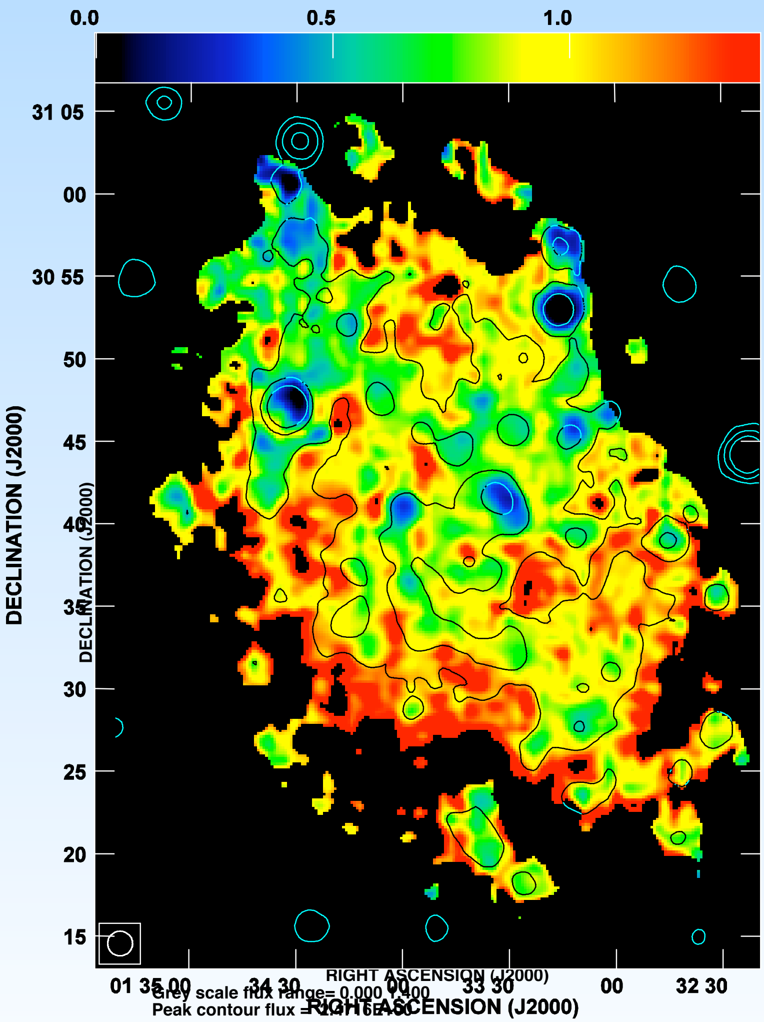
λ3.6 cm

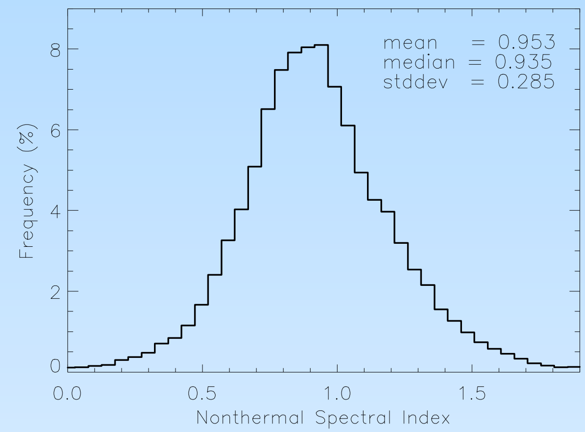
Nonthermal emission



Total thermal fraction = 51.4 % ± 10.6 %

Variation in the Synchrotron Spectral Index





- patchy distribution
- α≈0.6 in parts of spiral arms and the central region: injection of CRe by e.g. SNRs
- α=1.0 ±0.1 in between the arms and the outer parts: Synchrotron (+inverse Compton) energy loss of CRe

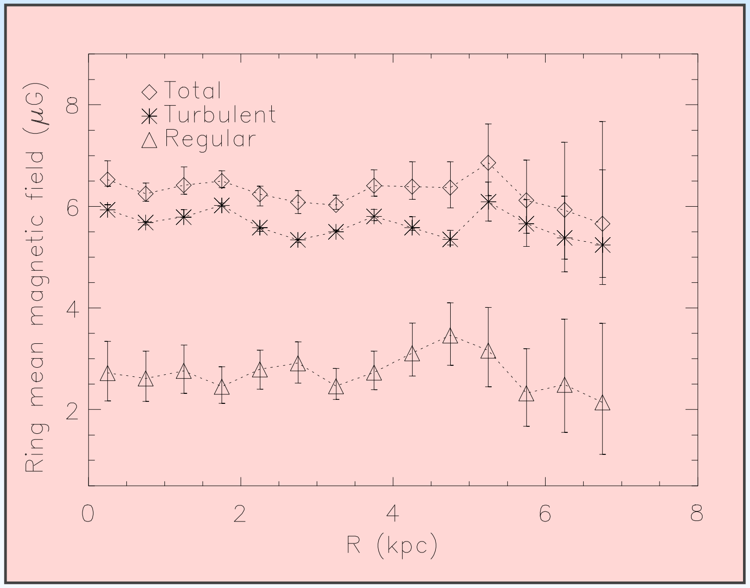
Magnetic Fields in M33

Equipartition magnetic field strengths:

Energy equipartition between magnetic field and cosmic rays: $B^2 \propto n_{CR}$

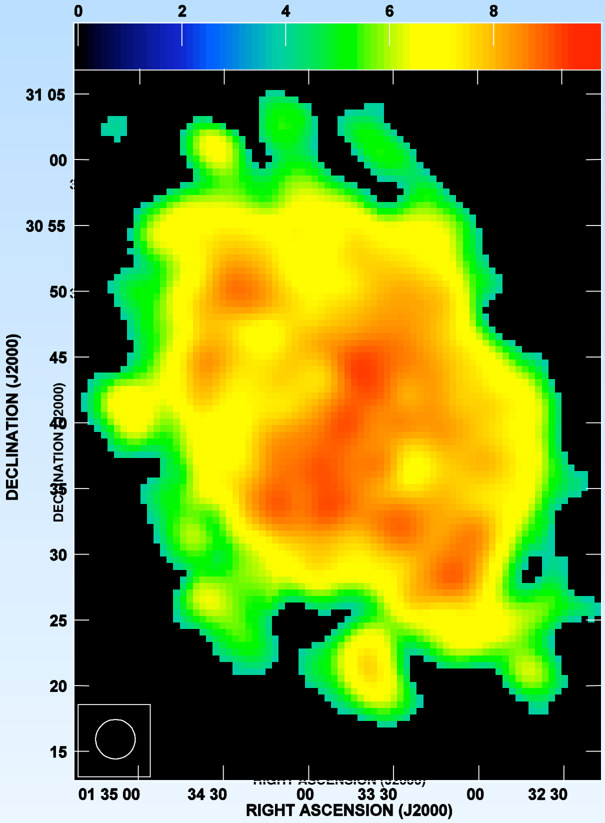
Regular field strength ≈ 2.5 μG

Total field strength ≈ 6.5 μG



(Tabatabaei et al. 2008)

Turbulent field strength



Scale lengths :
CRe ≈ 12 kpc
B ≈ 24 kpc

Magnetic Fields in M33

Measured polarization angle:

$$\phi = \frac{1}{2}\tan^{-1}\left(\frac{U}{Q}\right)$$

Intrinsic polarization angle: ϕ_i

Faraday rotation measure:

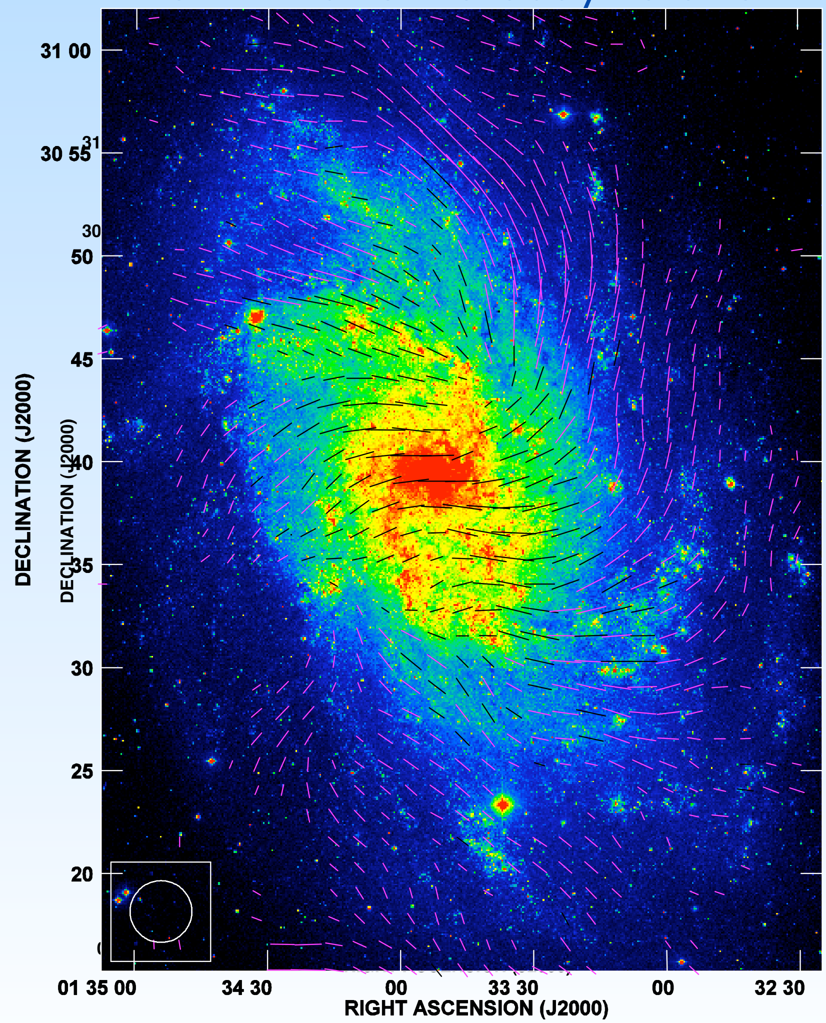
$$RM \equiv \frac{\phi - \phi_i}{\lambda^2} \approx \int B_{\parallel}\, n_e \, \mathrm{d}l$$

$$RM = RM_{\mathrm{i}} + RM_{\mathrm{fg}}$$

Recent galactic RM surveys
(Johnston-Hollitt et al. 2004):

$$RM_{\mathrm{fg}} = -55 \pm 10 \ \mathrm{rad/m^2}$$

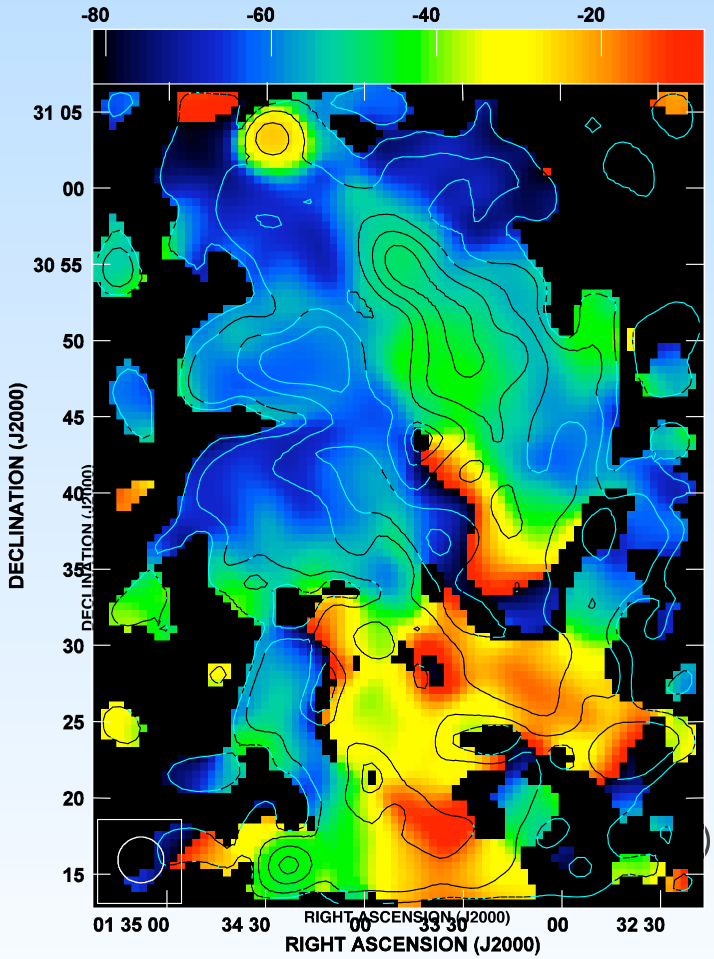
Optical image with B–vectors (3.6cm PI)
corrected for Faraday rotation



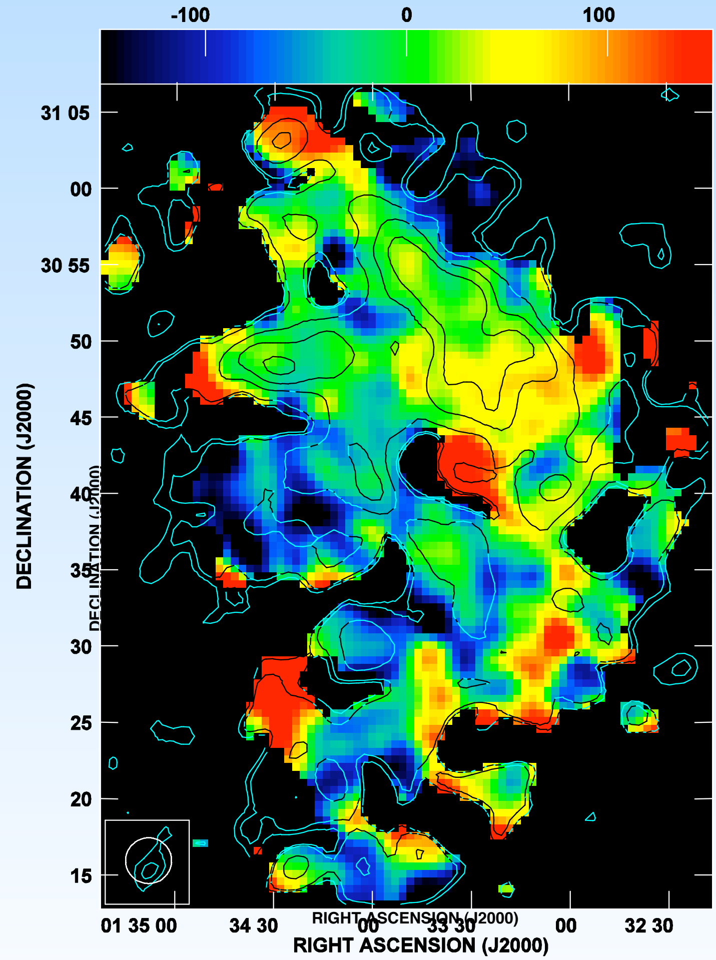
Magnetic Fields in M33

Faraday Rotation

$RM(3.6-20)$ (rad/m^2)



$RM_i(3.6-6.2)$ (rad/m^2)



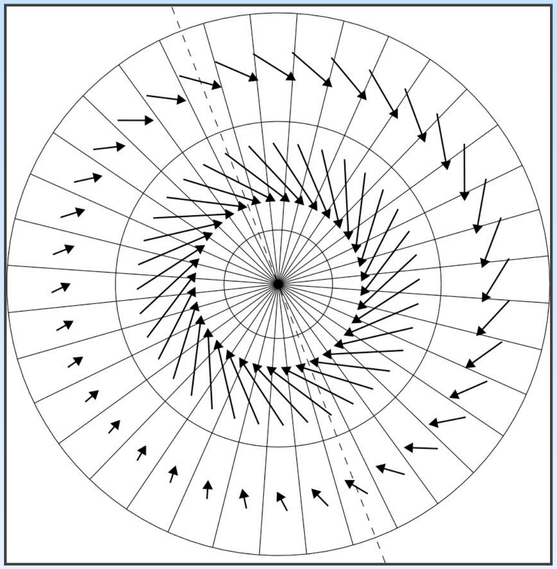
Magnetic Fields in M33

•3-D model: the cylindrical components of the regular field in the disk of M33 is represented in terms of Fourier series in azimuthal angle (m: Fourier mode)

•The model fitted to the observed polarization angles in sectors of 10° opening angle and 2 kpc radial width, in range of 1< R < 5 kpc, can best reproduce the polarized intensity if a combination of both horizontal (m = 0: axisymmetric, m=1:bisymmetric) and vertical (m=z0+z1) Fourier modes are used.

m = 0 + z0 +z1, 1 < R < 3 kpc
m = 0 + 1 + z1, 3 < R < 5 kpc

Modeled regular field projected in a face-on view



Origin of the field vertical to disk?

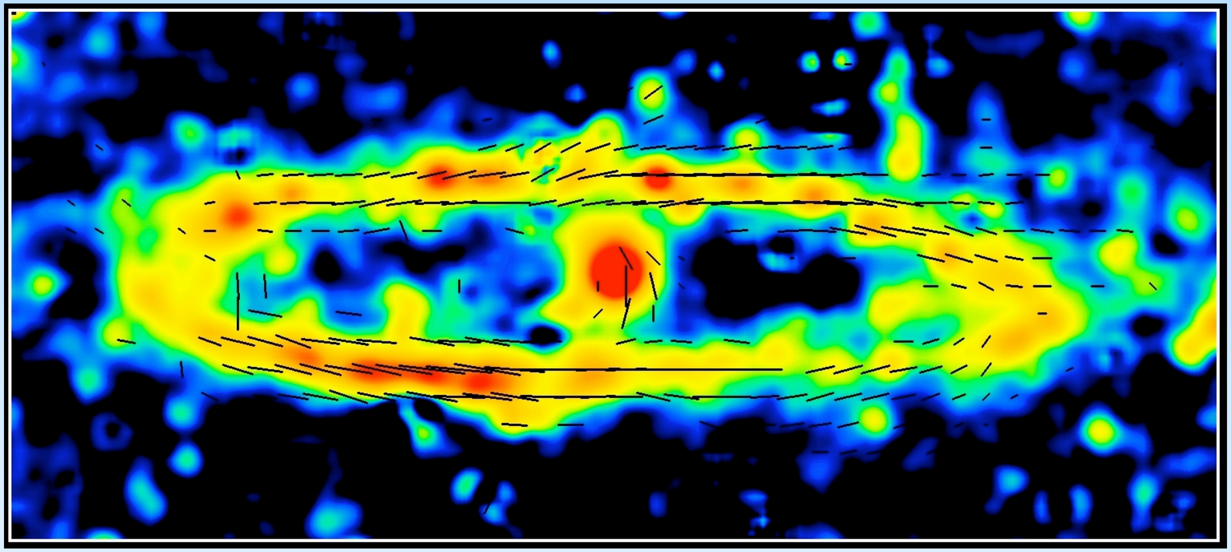
-Local phenamena connected to star formation activities?

-Global phenomena e.g. warp? (strong Bz along the major axis already exist)

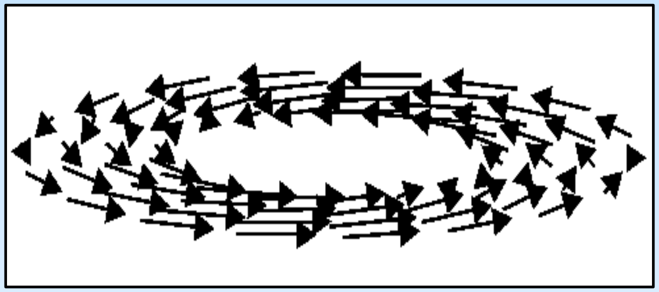
Magnetic Fields in M33

Comparison with M31

Total radio emission and B–vectors at 6cm



The classical dynamo case (m=0), field parallel to the plane



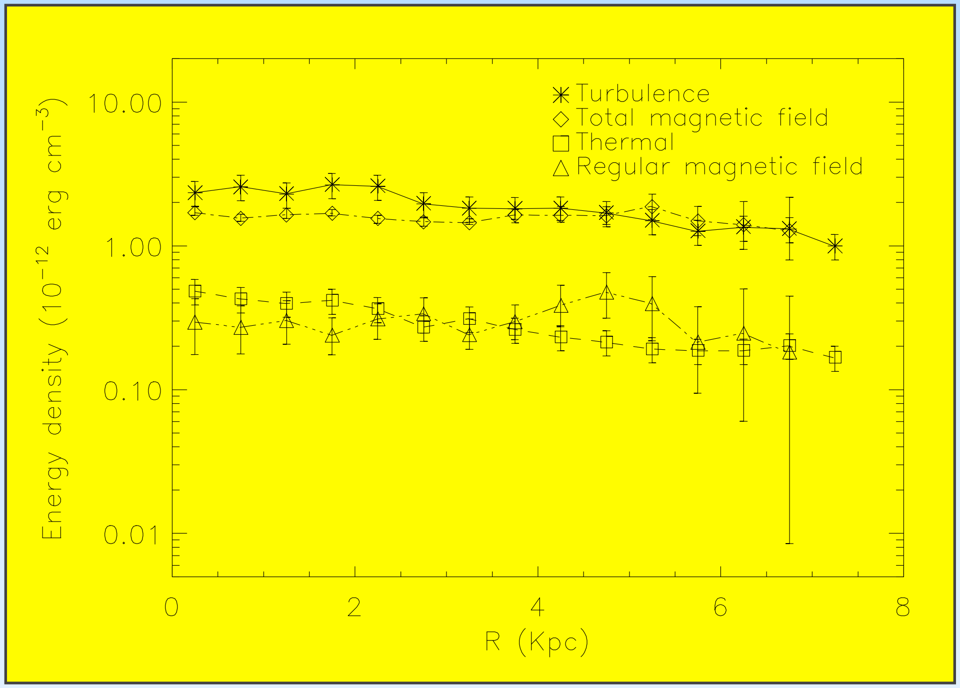
Fletcher et al. 2004

In M31:

- Total field strength ≈ 7 μG
- Regular field strength ≈ 5 μG
- Axisymmetric field with small pitch angle
- Fast diffusion of CR electrons

Magnetic Fields in M33

Energy Densities



$$U_B = B^2 / 8\pi$$

$$U_{Thermal} = \frac{3}{2} \langle n_e \rangle \, k.\, T_e$$

$$U_{Turbulence} = \frac{3}{2} \langle n_{\text{neutral gas}} \rangle \, k.\, T$$

$U_{Turbulence} \approx U_B$:

--> generation of interstellar magnetic fields from turbulent gas motions.

$U_B > U_{Thermal}$:

--> ISM in M33 can be characterized by a low-β plasma (as in MW, Cox 2005)

$U_{Turbulence} > U_{Thermal}$:

--> ISM is dominated by supersonic turbulence (as in NGC6946, Beck 2007)

Summary

•Thermal and nonthermal radio continuum emission:

With a smoother distribution than the thermal, considerable nonthermal emission from spiral arms and starforming regions (30% - 60% of total emission at 3.6cm)

•Variation of the synchrotron spectral index:

For the first time, a map of the nonthermal spectral index shows energy loss of CRes when diffusing away from starforming regions.
R> 4.5 kpc: synchrotron and inverse Compton losses
R< 4.5 kpc: injection by massive stars and energy loss by a mixture of leakage and synchrotron losses

Summary

• Magnetic fields :

-The 3-D structure of the regular magnetic field with a significant axisymmetric mode (m=0) indicates the galactic dynamo action in M33.

-The average equipartition strengths of the total and regular magnetic fields are ≈6.4 and 2.5 μG. Strong turbulent magnetic fields (>7μG) occur in active star forming regions.

-The energy densities of the magnetic field and gas turbulence are about the same: generation of interstellar magnetic fields from turbulent gas motions.

-The vertical magnetic fields, found through modeling, is possibly due to both global (e.g. M33's warp or interaction with M31) and local (e.g. star formation activities) phenomena. The warp of M33 can better explain the origin of the vertical field in the outer ring (3-5 kpc).

Open Questions

- Magnetic fields controlling SFR? Magnetism at smaller scales?

Higher resolution RC (e.g. EVLA, SKA), polarization studies of dust (e.g. ALMA)

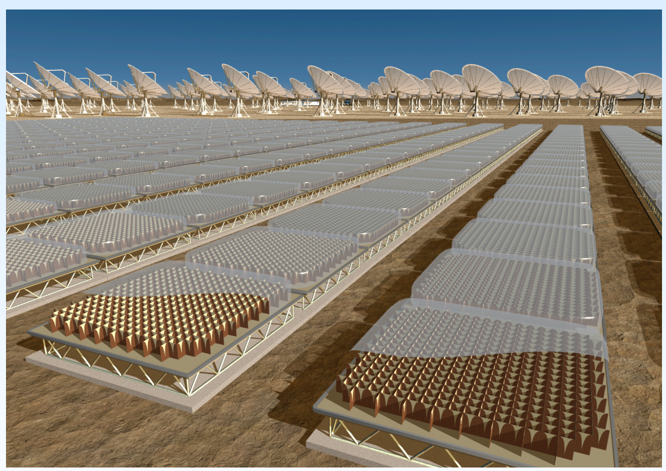
- Magnetic fields traced in the outer M33? Distribution of older CREs?

Lower frequency RC gives extended view of M33 in synchrotron, not contaminated by thermal emission (e.g. LOFAR)

- Strong depolarization in the south of M33?

RM synthesis with multi-channel polarimeters (e.g. EVLA, LOFAR)

λ: [60 - 670] μm



λ : [1 - 400] cm

λ : [1.2 - 10] m