Velocity Structures in the ISM

Phases of the ISM, 2013 MPIA summer conference

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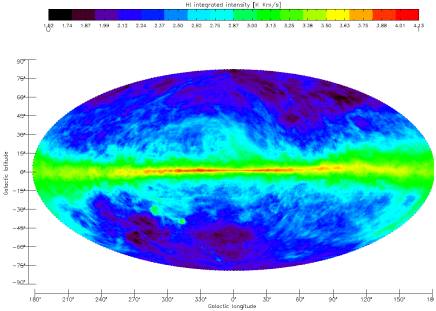
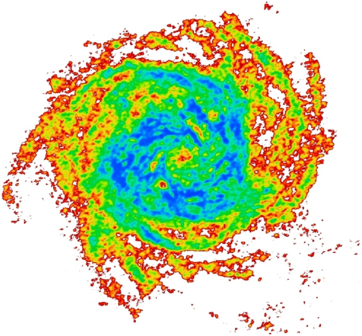
Milky Way (LAB) NGC 628 (THINGS)





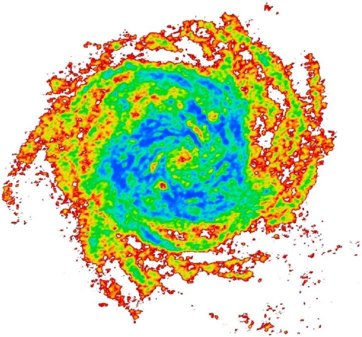
21 cm

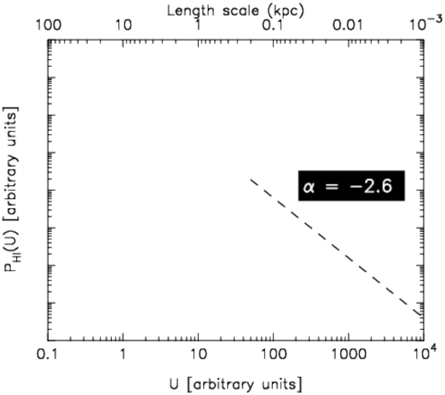
Statistical Measures

Statistical measures of how much fluctuations of a given scalar quantity is there.

- **Power Spectrum [$P(U)$]:**
  Function of inverse angular scales
  Power Spectrum
- **Structure Function [$SF_2(\theta)$]:**
  Function of angular scales
  Structure Function

21 cm



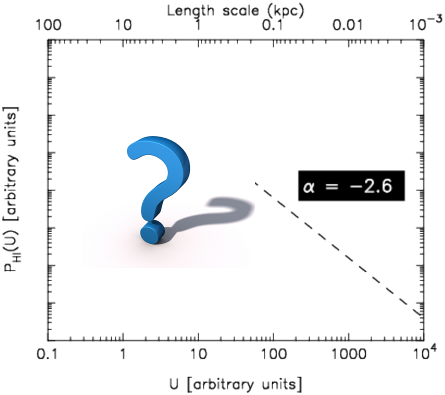


Green 1993, MNRAS, **262**, 327

Crovisier & Dickey 1983, A&A, **122**, 282

Power Spectrum Turbulence

- Power spectrum is power law ($P_{\rm HI}(U) = A\,U^{\alpha}$) at length scales ~ 1 pc to ~ 200 pc ($\alpha \sim -2.6$) indicating scale invariant structures.
- These structures are believed to be produced as a result of compressible turbulence in ISM driven by supernovae shocks and self gravity of the gas.



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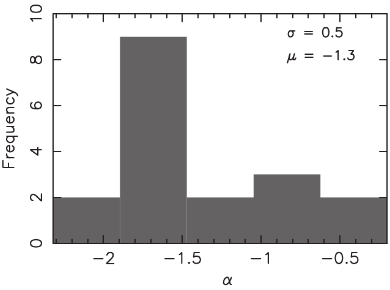
- These structures are believed to be produced as a result of compressible turbulence in ISM driven by supernovae shocks and self gravity of the gas.
- What happens at larger length scales ? ($\sim 1 - 10$ kpc or higher)

Power Spectrum of the THINGS Galaxies: Slope (α)

$$P_{\mathrm{HI}}(U) = AU^{\alpha}$$

- We estimate the power spectrum of 18 galaxies taken from the THINGS [a].
- The power spectrum for all cases came out to be power laws at length scales ranging from 600 pc to 16 kpc.
- Most of the galaxies in the sample have α value in the range -1.5 to -1.8.

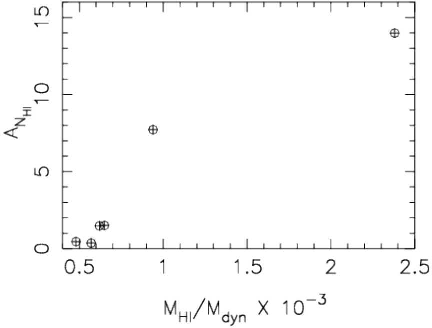
[a] The HI Nearby Galaxy Survey, Walter et al. (2008)



Dutta et al. (2013), NewAst, **19**, 89

Power Spectrum of the THINGS Galaxies: Amplitude (A)

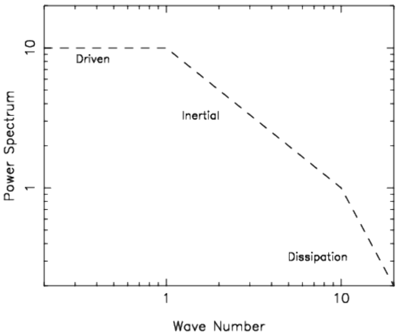
$$P_{\rm HI}(U) = AU^{\alpha}$$



Dutta et al. 2013, under revision MNRAS Lett.

- We estimate the column density power spectrum of 6 galaxies taken from the THINGS.
- We found that the fluctuation amplitude is one order or less than the mean column density in the spiral galaxies.
- The power law amplitude is apparently correlated with the gas mass fraction of the galaxies.

Density VS velocity statistics



- K41 (incompressible): Turbulence driven at large scale, energy cascades to the dissipation scale and dissipates. Power spectrum of velocity fluctuation assumes power law with slope $-5/3$.
- Compressible case: Similar arguments holds for density weighted velocity spectrum.
  see Federrath et al. (2013)
- So far we have talked about the (column) density spectrum only, it would be important to estimate the velocity statistics.

Density VS velocity statistics

- Lazarian and Pogosyan have shown in 2000 that the velocity structures in our galaxy can be estimated from the frequency dependence of the density power spectrum.
- Slope of the power spectrum is affected by the velocity spectrum slope when the width of the velocity slice used to estimate it is smaller than the turbulent velocity dispersion.
- It is not straight forward to apply this method for external galaxies.

Basic idea

$$V_{\textsf{LOS}}^{(\mathrm{obs})}(\vec{\theta}) \;=\; V_{\textsf{LOS}}^{(\mathrm{rot})}(\vec{\theta}) \;+\; V_{\textsf{LOS}}^{(\mathrm{fluc})}(\vec{\theta})$$

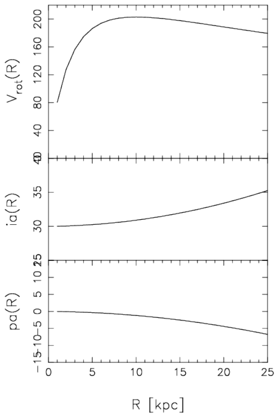
- Use moment 1 map to estimate the rotation curve for the external galaxy in question.
- Subtract the tangential velocity corresponding to rotation curve from the velocities in the moment 1 map to get the velocity fluctuation map.
- Use the fluctuation map to estimate the statistics.

Step by step

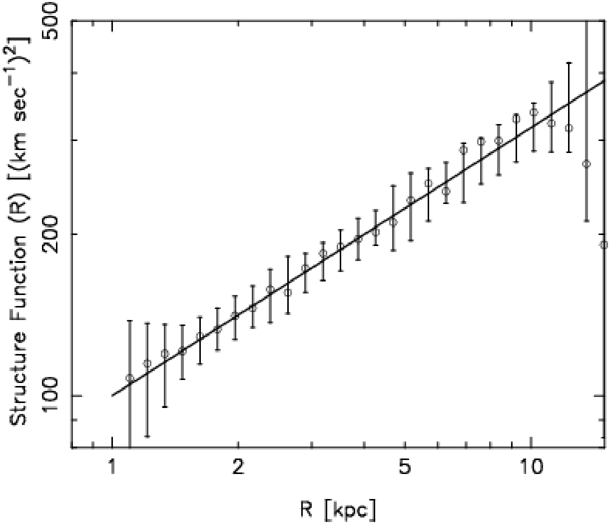
- Use AIPS to model the rotation curve using tilted ring model fit to the data (moment 1 map). This gives us the velocity, inclination angle and position angle of the rings at different distances from the dynamical centre of the galaxy.
- Generate several realizations of the fluctuation map using the rotation curve, inclination and position angle information and the moment 1 map.
  (We assume that the rotation velocity, position and inclination angles are Gaussian distributed with the mean and sigma from the tilted model fit.)
- Estimate structure function for each fluctuation maps. The mean and the standard deviation of velocity fluctuation is estimated from the mean and standard deviations of the estimated structure function across the different realizations.

Simulations

- Always use simulations to verify the method you have proposed.
-
    - Rotation curve: Brandt profile
    - Inclination and position angle: third order polynomial
    - Velocity fluctuation: with known structure function (power law)
- So far we have talked about the (column) density spectrum only, it would be important to estimate the velocity statistics.

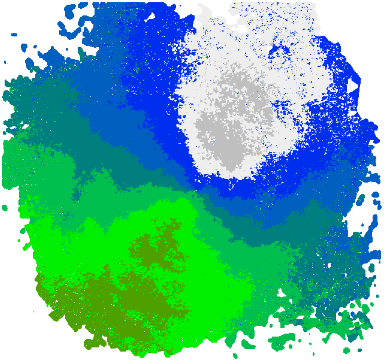


Simulations: Input vs Output

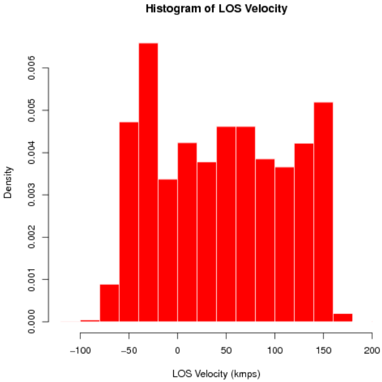


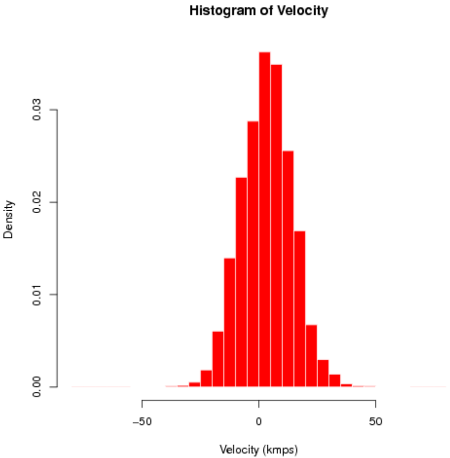
DATA(THINGS): NGC 6946

- **Distance** : 5.9 MPc
- **ia** : 33 degrees
- **pa**: 243 degrees

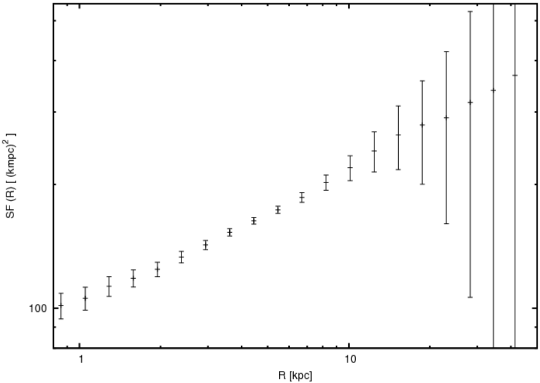


NGC 6946 (THINGS)





NGC 6946(THINGS): Results

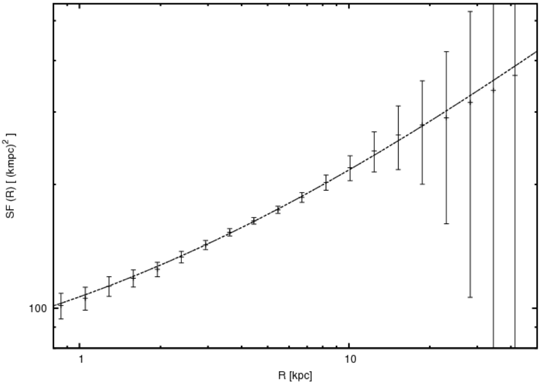


NGC 6946(THINGS): Results

$$S(R) = S_0 + S_1\, R^{\beta}$$

$S_0 = 58 \pm 10$ (km s^{-1})^2
$\delta V_? = 7.6$ km s^{-1}
$S_1 = 48 \pm 8$ (km s^{-1})^2
$\delta V_{turb} = 6.9$ km s^{-1}

$$\beta = 0.5 \pm 0.1$$



...Results

- Scale invariant Velocity structures: More direct indication of turbulence: long range of length scales [1 to 10 kpc]
- Slope of the spectrum is ~ 0.5.
- Column density structure function slope: ~ 0.5
  Turbulence velocity structure function slope: ~ 0.5
  $=>$ Not Self gravity: not unexpected !!
- Turbulence velocity dispersion at 1 kpc scales ~ 7 km s^{-1}, at 10 kpc scales it would be ~ 20 km s^{-1}.

...Results: Connection to phases of the ISM

$$S(R) = S_0 + S_1\, R^{\beta}$$

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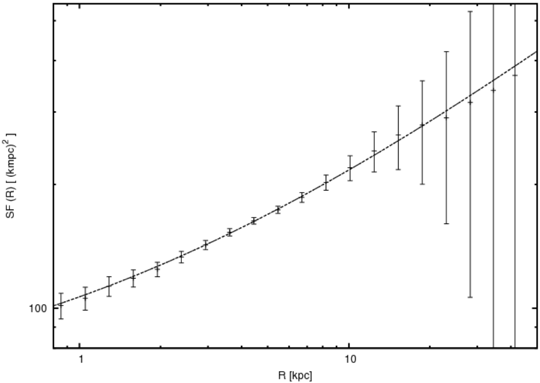

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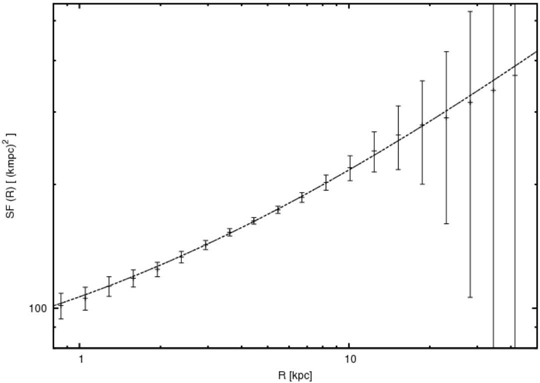
Warm Neutral Medium ???



What have we learned

- The velocity structure is scale-invariant (power law structure function with a slope ~ 0.5) : what you expect for turbulent medium.
- The scale invariant velocity fluctuation at 1 to 10 kpc scales: remember there is large scale scale-invariant structures at the same scales.

What have we learned

- The velocity structure is scale-invariant (power law structure function with a slope ~ 0.5) : what you expect for turbulent medium.
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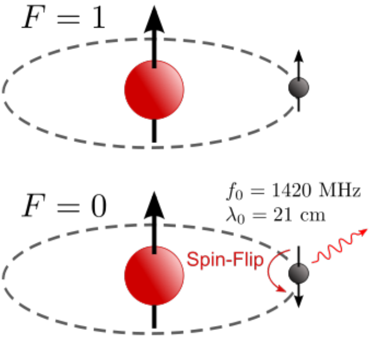
- **WNM:** We see a random velocity component that has not scale structures, which is most likely the WNM. This can be used to access the WNM temperature at different regions (very low resolution)
- **Generating mechanism:** What creates these density and velocity fluctuations ?

Go back; Go back: Go back

GO BACK

Hyperfine Structure



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$A_{21} = 2.85 \times 10^{-15}$ sec^{-1}
extremely rare in laboratory

Specific Intensity

H I Emission

Specific intensity of H I 21 cm radiation generated from a gas of column density $N_{\mathrm{HI}}(\vec{\theta})$ in the direction $\vec{\theta}$ in the sky

$$I_{\mathrm{HI}}(\vec{\theta},\nu) \;=\; \left(\frac{3A_{21}\,h\nu_e}{16\,\pi}\right)\,\phi(\nu)\,N_{\mathrm{HI}}(\vec{\theta})$$

ν_e frequency of emission
$\phi(\nu)$ line shape function.

H I Absorption

$$I_{\mathrm{Observed}}(\nu) \;=\; I_{\mathrm{Cont}}(\nu)\,e^{-\tau(\nu)} \tag{1}$$

τ optical depth back

Power Spectrum

Intensity distribution in the sky $I(\vec{\theta})$

$$I(\vec{\theta}) \;=\; I_0 \;+\; \delta I(\vec{\theta})$$

In Fourier Space

$$\delta\tilde{I}(\vec{U}) \;=\; \int\int d\,\vec{\theta} e^{-2\,\pi\,i\,(\vec{U}.\vec{\theta})}\,\delta\,I(\vec{\theta})$$

Power spectrum of $\delta I(\vec{\theta})$

$$P_{\rm HI}(U) \;\propto \langle\mid \delta\tilde{I}(\vec{U}) \mid^2\rangle$$

U is the inverse angular scale $\frac{1}{|\vec{\theta}|}$.

back:outline back: statistics

Power Spectrum Estimator

- The radio interferometers (like GMRT [a], VLA [b] are used to observe external spiral and dwarf galaxies.
- Radio interferometers measures visibilities $\mathcal{V}(\vec{U})$, which are Fourier transform of sky brightness distribution $I(\vec{\theta})$.
- We correlate the visibilities to measure power spectrum.

$$\mathcal{V}(\vec{U}) = \int d\,\vec{\theta} e^{-2\pi\,\vec{U}.\vec{\theta}}\, I(\vec{\theta})$$

$$P_{\rm HI}(U) \propto \langle \mathcal{V}(\vec{U})^{*} \mathcal{V}(\vec{U}) \rangle$$

$$P_{\rm HI}(U) \propto U^{\alpha}$$

[a] Giant Meterwave Radio Telescope
[b] Very Large Array, New Mexico

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Structure Function

Any scalar quantity in the sky $A(\vec{\theta})$

$$A(\vec{\theta}) \;=\; A_0 \;+\; \delta A(\vec{\theta})$$

Structure function (of order 2) is defined as

$$\begin{aligned} SF_2(\vec{\phi}) &= \left\langle \left[A(\vec{\theta}+\vec{\phi}) - A(\vec{\theta}) \right]^2 \right\rangle \\ &= \left\langle \left[\delta A(\vec{\theta}+\vec{\phi}) - \delta A(\vec{\theta}) \right]^2 \right\rangle \end{aligned} \tag{2}$$

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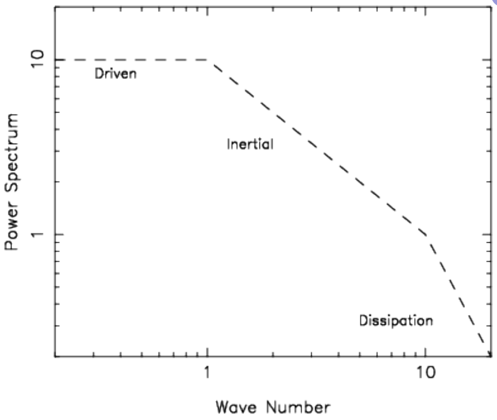
Turbulence Power Spectrum



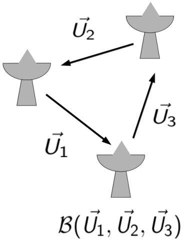
back:turb

Bispectrum Estimation

Bispectrum of a scalar stochastic field $A(\vec{\theta})$ is defined as

$$\mathcal{B}(\vec{U}_1, \vec{U}_2, \vec{U}_3) \;=\; \delta_D(\vec{U}_1 + \vec{U}_2 + \vec{U}_3)\, \langle \tilde{A}(\vec{U}_1)\tilde{A}(\vec{U}_2)\tilde{A}(\vec{U}_3)\rangle$$

$\vec{U}$: inverse angular scale (baseline)
$\tilde{A}(\vec{U}_2)$: Fourier transform of $A(\vec{\theta})$.



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