Study of Structure and Dynamics of the InterStellar Medium in Nearby Spiral Galaxies

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by

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Chapter 6

Conclusions and Summary

Spiral galaxies are complex gravitationally bounded systems of diverse structures like stars, gas clouds, dust and many more. These galaxies for a long time remains as stable disc by fighting against the gravitational force of attraction with the help of different dynamical phenomena like rotation, high gas dispersion etc in their interstellar medium (ISM). The formation of various structures in ISM is eventually the result of a tug of war between these dynamics and gravity at various length scales. Hence understanding the evolution of structure and dynamics in the ISM are critical for establishing a fundamental theory on galactic formation and evolution. This thesis is trying to study the various structures and involved dynamics in the ISM of nearby spiral galaxies with the help of observational data on gas and stellar distribution in them. Our main findings and inferences are listed below.

- Various two point functions are the useful statistical estimator for coherent scale invariant isotropic structures in the H I disc of galaxies. In the case of the external disc galaxies, the statistics emerging directly from the observed visibilities has to be studied. Through controlled simulation tests, we show that the H I two point statistics like power spectrum can be estimated unbiasedly from directly measured visibilities in radio interferometric observations. The image based estimators of the two point statistics were found to be biased. On the other hand, we found with careful image reconstruction, large scale one point properties like the various radial profiles etc can be estimated from the image.

- The energy input and injection scale of the ISM turbulence can be inferred from the turbulent column density and velocity fluctuation power spectrum. We implement a new estimator based on visibility moments, Visibility Moment Estimator (VME) of the H I column density and velocity fluctuation power spectra. We combine new high resolution observations with existing THINGS data and use VME for two spiral galaxies NGC 5236 and NGC 6946. The column density and velocity power spectra measured show power law in both galaxies for more than one decade of length scales. This provides evidence for large scale turbulence cascade from a few kpc to a few hundred pc from the scales of galactic size ($\sim 11 - 6$ kpc) to the scales of $\sim\ 300 - 100$ pc.

- Inferring from the slopes of the power law power spectra, we are able to conclude that measured turbulence in NGC 5236 is possibly driven by a compressive force. For the galaxy NGC 6946, we find that the turbulence therein is driven most likely by a combination of compressive and solenoidal forces. Conclusions on the observed turbulence in two galaxies are given below.

  - **NGC 5236** : The observed turbulence is found to be driven at around 6 kpc scales and cascades down to scales of $\sim$ 300pc. We found that the average scale height of the disc is $<$ 300pc. The Jeans length estimated from the density and velocity fluctuations at these scales suggests that the energy included may be from the gravitational instability or self-gravity in the disc.

  - **NGC 6946** : The energy cascade is present to the scale of $\sim$ 170 pc in the galactic disc, with the slope of power law indicating that the forcing of turbulence is a combination of compressive and solenoidal. The solenoidal part of the forcing can be a result of the differential rotation coupled with the strong magnetic fields in the spiral arms of NGC 6946.

Dutta et al. (2013) estimated H I intensity fluctuations power spectrum of 18 spiral galaxies and all of them have power law power spectrum in length scales from $\sim 300pc$ to ~ 16 kpc. The 50% of the sample galaxies have column density power spectrum slope ranging from -1.9 to -1.5 with a mean value of slope -1.3. Comparing with simulated results on compressive turbulence (density power spectrum of slope ~ -1.44) and observational evidence from NGC 5236, we suggest that compressive turbulence either by gravitational instability or self-gravity could be the common driving force for ISM turbulence in spiral galaxies. They also find that NGC 925, NGC 2403 and NGC 3621 galaxies have column density power spectrum with slope ~ -1.0. These galaxies are likely to have a mixture of compressive and solenoidal forcing with the solenoidal part possibly coupled with magnetic fields.

- The role of turbulence in influencing the gravitational instability to lead star formation was investigated, by doing disc instability analysis in three spiral galaxies. Two galaxies NGC 5236 and NGC 4736 provide evidence, that turbulence in ISM induces fragmentation which eventually speeds up the collapse of unstable regions to form new structures and hence promote star formation. The galaxy NGC 3351 shows a different scenario, where the gravitational instability leads to unstable regions, but not high star formation. The positive correlation between the slope of the column density power spectrum of these galaxies and star formation rate per unit area suggests that the onset of turbulence fragmentation is critical for star formation. This analysis demonstrates how star formation activity can noticeably influenced by the presence or absence of ISM turbulence.

- Turbulent velocity dispersion is expected to quench star formation in the disc galaxies. As we do not find any direct evidence of quenching due to the velocity dispersion in the disc of our galaxies to a length scale of about 300 pc, it suggests that this effect happens at much smaller scales.

- The galactic disc is so enriched that in addition to these turbulent generated structures which are generally isotropic in nature at the length scales we probe, anisotropic structures in density and velocity space are also common. Bending of the galactic disc entirely or even partially, can happen due to tidal interaction from satellite or companion galaxies, intergalactic winds etc. This results in the formation of wavy undulations in the galactic disc, which are termed as bending waves or corrugations. Such anisotropic fluctuations are rarely detected in external spiral galaxies due to limitations by inclination effect and their lower fluctuation amplitudes. This limitation can be overcome by tracing the kinematic signatures of bending waves. Using harmonic decomposition, we estimated the different Fourier modes of these fluctuations from archival observations of the H I in six nearby spiral galaxies. All galaxies are found to be perturbed vertically about the disc plane. All sample galaxies show a combined kinematic signature of superposition of a few lower-order bending modes, suggesting that bending waves are a common phenomenon. The mode $m = 2$ is the most common that appears in all samples.

Our investigations demonstrate that the structure and dynamics in the ISM of spiral galaxies are complicated and diverse. In between a tug of war played by gravity and dynamics, turbulence was found to play a significant role in cascading energy down from the largest scales and then regulating star formation. We believe this thesis establishes the role of large scale turbulence cascade in galactic dynamics. Though ISM turbulence is a common phenomenon in spiral galaxies, the driving mechanism is likely to be not the same for all galaxies. This thesis does the groundwork to establish a methodology to probe the large scale turbulence cascade in external spiral galaxies. Using these methods we find the nature of large scale turbulence cascades in two external spiral galaxies.

Hence the comprehensive study of turbulence mechanisms using a large number of sample galaxies would lead to a much stronger understanding of ISM turbulence. With the commissioning of an upcoming telescope-like Square Kilometer Array (SKA), it would be possible to perform these investigations with highly sensitive and high resolution observations of a large number of spiral galaxies. The newly understood large scale turbulence cascade and the other anisotropic structures studied in this thesis are just an indication of a lot that is yet to be understood about the ISM structure and dynamics of external spiral galaxies. We would like to work in this direction to reveal more mysteries in future.