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

Thesis submitted in partial fulfillment

for the Award of Degree

DOCTOR OF PHILOSOPHY

by

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To my loved ones . . .

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After a couple of sleepless nights and stressful months, I think this is the time where I need to sit and have some rewind to my life so far. I believe this could be the best chance where I can remember a few persons that have influenced me in this short life.

If I go back to my childhood, I used to spend my entire time with my grandparents Late. Mr Gopinathan and Mrs Hymavathiamma. I always remember the precious moments that I spent with them during my childhood. Though as a mischievous kid I used to always eat their head off, I can understand now how much they enjoyed it then. I was lucky to be their only grandchild until my seventh age and I really enjoyed that privilege. I remember my maternal grandfather Late Mr Pankajakshakurup, who was my first childhood friend or pal whom with I played a lot, unfortunately for a small period. My grandmother Late Mrs Ponnama used to advise me a lot telling 'Don't do this' or 'Do this'. Though I don't like them at all as a child, I can understand her feeling of care towards me that drives her to say those. I always miss those nice times which I spent with my two grandmothers, hearing their childhood stories.

The void which I used to feel from not having a sibling for the first seven years of my life, was compensated by a few people who are close to my heart. Apart from my grandparents, one major person that made those days sweet and precious is my maternal uncle Mr Balachandran. My main motivation for visiting my mother's home is that I can meet my uncle and play with him. He used to take me to a lot of places in his RX tiger bike where me sitting on top of it and I literally feels like a King while riding. Another person that whom I always like to chat with is my paternal Aunt, Mrs Rekha. I remember the day when she came to our family as a new bride where I felt initially complete strangeness toward her. But now, I am amazed by the transformation that she created in me so that rather than my Uncle Mr Balakrishnan, I feel close to her.

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Meera Nandakumar

D/o Nandakumar P G

Abstract

Spiral galaxies are composed of stars and interstellar medium (ISM) residing in a dark matter halo. They are very much dynamically active and are the playgrounds for the ISM to give birth to stars. The large scale distribution in dark matter halo, differential galactic rotation, interaction with satellite galaxies, star formation and its feedback, all give rise to isotropic and anisotropic density and velocity structures in the ISM. The interstellar medium acts as a compressible fluid with turbulent flows that later give rise to scale invariant density and velocity structures. The density structures give rise to fragmentation in the gas helping it to collapse. On the other hand, the turbulent dynamics raise the pressure and at small clumps, collapses are lengthened. Such scale invariant structures in both velocity and density have been seen observationally in our Galaxy and its satellites at scales of the order of a few astronomical units to a few hundreds of parsec (Crovisier and Dickey, 1983; Green, 1993). Recent observations in nearby spiral galaxies have established the existence of scale invariant coherent density structures at the scales of a few kiloparsecs, almost at the scale of the galactic discs (Dutta et al., 2013). The observed structures in our galaxy at scales of a few hundreds of parsec and lower are attributed to compressible fluid turbulence generated by the supernovae feedback. However, related dynamics and the generation mechanism of the large scale structures probed recently in external spiral galaxies are now well established. In this thesis, we design and implement various statistical estimators and use them to investigate the large scale structure and dynamics of the ISM in these spiral galaxies. We comment on the driving mechanism behind the large scale structures based on our observations and access their relation to star formation.

We use radio interferometric observation of H I 21-cm emission line as a tracer of the ISM. Radio interferometers measure visibility function, roughly the Fourier transform of

the sky brightness distribution. The visibilities are measured only at discrete points in the baseline plane, the Fourier conjugate to the angular separation in the sky. To probe the structure and dynamics of the ISM, we need to estimate the large scale dynamics and morphology of the gas. The imprint of turbulence can be traced through the two-point statistics of the density and velocity, like their spatial power spectrum. The limited measurements of visibility create challenges to estimate various statistics of the density and velocity unbiasedly. In this thesis, we first use simulation of radio interferometric observations of external spiral galaxies to investigate the efficacy of estimation of the column density distribution from the reconstructed images from visibilities. We also compare the image based and visibility based column density power spectrum estimators to access their relative merits in this context. We find that the Natural weighting scheme in the CLEAN deconvolution algorithm unbiasedly estimates the large scale distribution of the H I , whereas to estimate the power spectrum direct use of visibilities gives an unbiased result.

Turbulence is a stochastic random process which creates scale invariant structures in density and velocity that can be quantified through the spatial power spectrum measurements of density and velocity. The power spectrum of turbulence generated structures follows a power law, with its slope indicating the nature of turbulence. Combined knowledge of density and velocity power spectrum lets us infer the energy supply and driving mechanism. Following the idea of Dutta (2016) we develop and implement Visibility Moment power spectrum Estimators (VME) of H I column density and line of sight velocity power spectrum directly from the observed visibilities. We measured the column density and the line of sight velocity power spectrum of spiral galaxies NGC 5236 and NGC 6946. We present here the evidence of large scale energy cascade in these galaxies observed in more than one decade of length scales between $\sim$ 100 parsecs to 15 kiloparsecs. We find that the compressive forcing is responsible to drive the turbulence cascade at the scales of

kiloparsec and higher in NGC 5236. While a combination of solenoidal and compressive force acts a generating mechanism for the turbulence in NGC 6946. The cascade brings down energies to the scales of 100 pc which is comparable to the energies injected by supernovae feedback.

We review the instability of a star-forming disc in presence of turbulence (Leroy et al., 2008). The instabilities are assessed through modified Toomre criteria of two fluid disc models incorporating effects of turbulent generated log-normal H I density distribution. We choose a sample of three galaxies, NGC 4736, NGC 3351 and NGC 5236 with similar stellar and gas mass and velocity dispersions but different disc scale length and star formation rates per unit area. We find that the H I is unstable at scales greater than a few kiloparsecs in the regions with high H I column density, at smaller scales the correlation between high H I column density and instability dies down indicating conversion of H I to the molecular cloud. At small scales, we also see more fragmented regions of instabilities commensurate with the high star-forming regions. We observe that for NGC 3351, even at small scales the high ISM column density regions do not form stars effectively. Comparing the column density power spectrum slopes in these three galaxies we conclude that turbulent fragmentation has a significant role in inducing instabilities which eventually seed the star formation.

Several dynamical effects like interaction with satellite galaxies, accretion of the intergalactic medium, tidal effects etc create bending waves in the galactic discs. Observationally these are traced as corrugation in edge-on discs for density and in the face on stellar disc for velocity mostly in optical or infrared (Narayan et al., 2020; Sánchez-Gil et al., 2015). In this thesis, we investigate the corrugation in gas density and velocity using 21-cm observations of the galactic discs. With a sample of six nearby spiral galaxies, we estimate the multipole moments of the column density and line of sight velocity corrugation. We see all these galaxies are vertically perturbed indicating that corrugations or bending is a

common phenomenon. We also see that $m = 2$ is the dominant mode that forms around 50% of the identified modes in both density and velocity space. This probably suggests that $m = 2$ mode may be long-lived than the higher modes. Most of the anisotropies are also found near the $0.6R_{25}$ of the corresponding galaxies suggesting the likely cause of these structures is the gravitational interaction of the gas with the stellar disc.

This thesis establishes the origin and role of large scale turbulence cascade in the disc galaxies and explores vertical corrugations in the spiral galaxies. Some of the results presented here had indications in recent simulations of the discs, others need further theoretical study.

List of Symbols

Acronyms

Acronym	Full form
H I	Neutral hydrogen
H II	Ionized hydrogen
CO	Carbon Monoxide
PA	Position Angle
ISM	Interstellar Medium
SFR	Star Formation Rate
NGC	New General Catalogue
DDO	David Dunlap Observation
SMC	Small Magellanic Cloud
LMC	Large Magellanic Cloud
AIPS	Astrophysical Image Processing System
CASA	Common Astronomy Software Application
VLA	Very Large Array
GMRT	Giant Metrewave Radio Telescope
SKA	Square Kilometer Array
THINGS	The H I Nearby Galaxy Survey

Symbols

Symbols	Definitions
H_2	Molecular hydrogen
$\vec{U}$	Baseline in wavelength
ν	Observing frequency in Hz
$\vec{\theta}$	Angle in the sky measured from the centre of the galaxy
$V(\vec{U},\nu)$ or $V(\vec{U})$	Visibility
$V_j(\vec{U})$	jth moment of Visibility
$I(\vec{\theta},\nu)$	Specific Intensity
$M_j(\vec{\theta})$	jth moment of specific intensity
$\bar{I}_\nu$	Smooth part of $I(\vec{\theta},\nu)$
$\delta I(\vec{\theta},\nu)$	Fluctuating part of $I(\vec{\theta},\nu)$
$W(\vec{\theta})$	Window function
$A(\vec{\theta})$	Antenna primary beam
$\mathcal{N}(\vec{U})$	Noise at baseline $\vec{U}$
$I_C(\vec{\theta})$	Reconstructed image from measured visibilities
$P_{\rm HI}(\vec{U})$	H I column density Power spectrum
$P_C(\vec{U})$	Image Based density Power spectrum
$P_V(\vec{U})$	Visibility based density Power spectrum
$P_v(\vec{U})$	H I line of sight velocity Power spectrum
$1M_\odot$	Solar mass: $1M_\odot$ = 1.99×10^{30} kg

Symbols	Definitions
U_{min}	Minimum value of the baseline above which power spectrum is a power law
U_{max}	Maximum value of the baseline below which power spectrum is a power law
R_{min}	Minimum length-scale above which power spectrum is a power law
R_{max}	Maximum length-scale below which power spectrum is a power law
A	Amplitude of the power law
α	Power law index
c	Speed of light = 299792458 m/s
ν_0	Emission frequency of H I 21 cm line = 1420.40575 MHz
h_z	Scale height of the galaxy
$i_{\rm HI}$ or i	H I inclination angle
ω	Axisymmetric frequency of pertubation waves
κ	Epicyclic frequency
R	Galacto-centric radius
Q	Toomre Parameter
k	Wavenumber
Σ	Surface density
M	Mach Number
$1{\rm pc}$	1 parsec = 3.08×10^{16} m

Symbols	Definitions
$\mathcal{R}$	Ratio of the total intensity to the standard deviation of intensity fluctuations
R_{25}	Optical extent at which B band surface brightness is at the level of 25 magnitude arcsec^{-2}
G	Gravitational Constant, $6.6743 \times 10^{-11}\ \mathrm{m}^3\ \mathrm{kg}^{-1}\ \mathrm{s}^{-2}$
m	azimuthal bending mode
$\mathrm{\AA}$	unit of length, $1\mathrm{\AA} = 10^{-10}$ m

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