

Chapter 1

Introduction

The universe outside our home 'Earth' is vast and its boundaries are unknown. The Sun is just a star like many other billions of stars in our Galaxy, the Milkyway. A galaxy is a gravitationally bounded system of stars, gases and dust particles with a variety of interesting and complicated structures and dynamics. Earlier, it was thought that all the stars that are seen with the naked eye in the sky belong to our Galaxy and that is all there in the universe. Edwin Hubble discovered our neighbour galaxy Andromeda (M31) in 1925 and estimated the distance to the galaxy in later years (Hubble, 1929). Further studies on our Galaxy and M31 like nearby galaxies revealed different structural components present in the galaxies. Spiral arm or spiral structure where stars, star-forming regions, gases etc are concentrated is one of the major features in these type of galaxies. Existence of spiral arms were first hypothesized by Isaac Roberts and James Edward Keeler in 1890's (Keeler, 1899; Roberts, 1889). The first observational confirmation of the existence of spiral arms were done much later in our Galaxy by Morgan et al. (1953). With the initial discovery of 21-cm line (van de Hulst, 1951), various attempts were made to observe 21-cm line emission from the Galaxy and external galaxies and map their column density distribution. These studies revealed spiral structures in many galaxies including our own (van de Hulst, 1957). At the same time, more detection of other galaxies outside the Milkyway was

enabled by the emergence of various telescopes in different wavelengths. Based on the shape of galaxies that we see, Hubble (1927) proposed a galaxy classification scheme, where they are divided into major three types: elliptical, spiral and irregular. He also proposes subdivision to this type. Elliptical galaxies are ellipsoidal in shapes which lack structural features like spiral arms and are seen mostly larger in size. Most of the stars in these galaxies are old with very small star formation rates. On the other hand spiral galaxies are dynamically active ones, where stellar activity is high. The stars seen here are much younger ones compared to those found in elliptical galaxies. Spiral galaxies are circular disc like systems which have a bright nucleus at their centre. For a typical spiral galaxy, most of the stars are within a radius from 5 kpc - 20 kpc and disc thickness of the order of a few hundred parsec ¹. Our Galaxy and Andromeda are examples of spiral galaxies. Many spiral galaxies have a bar kind of structure in the centre of the galaxy. In such galaxies, spiral arms are originating from the two ends of the bar and the bar plays a crucial role in the dynamics of the galaxy. Irregular galaxies do not have noticeable shapes and lack spiral structures or a central nucleus. Like spiral galaxies they also have a lot of gases and dust, hence highly active in star formations. Hence these types of galaxies are also brighter. Among these different types of galaxies that we see, spiral galaxies are the most complex and have a long term stable morphology but possess a dynamically active system, where star formation activity is higher. It is believed that the spirals evolve through mergers and internal dynamics to eventually ellipticals. Understanding of the entire structure and dynamics of a spiral galaxy is the key to understanding galactic evolution.

Along with stars which comprise around 5% of total volume, spiral galaxies have a lot of gas and dust particles residing in their dark matter halo. The baryonic matter in the galaxy other than the stars is called the Interstellar medium (ISM). During the evolution of a star, it forms out of the gases and dust in ISM and during its different stages of life, the star emits its composition back to ISM through stellar winds, supernova events etc. Hence

¹1 parsec= 3.08×10^{16} meters

it is crucial to investigate the structure and dynamics of the ISM to understand the theory of star formation, stellar and galactic evolution. The major atomic composition of ISM is neutral hydrogen otherwise known as H I ($\sim 70\%$) and He ($\sim 28\%$). Hydrogen is also found to see in its ionized form, H II (Ellis and Hamilton, 1966) and in molecular form as H₂ (Ellis and Hamilton, 1966) in the ISM. The existence of diatomic molecules like CH, CN, CH⁺, OH, CO and several polyatomic molecules NH₃, H₂CO etc are confirmed through observations (McKellar, 1940; Weinreb et al., 1963; Wilson et al., 1970). Apart from the gas and molecular composition, ISM also has dust particles which are sometimes referred as interstellar dust (Grun et al., 1993). These are the solid phase of ISM, which play an important role in interstellar extinction, gas-phase element depletion etc. The gases in ISM exist in several thermal phases which have distinct density and temperature features. Earlier work by Field et al. (1969) introduced the ‘two-phase’ model of ISM, where cold neutral medium (CNM) and warm neutral medium (WNM) coexist in pressure and thermal balance. Later by McKee and Ostriker (1977) proposed a third phase, the warm ionized medium (WIM) which is hotter and with lesser density, formed mainly by supernova remnants. Further studies on the phases of ISM evolved to the latest five phase model of the ISM which constitutes the following components: molecular clouds, CNM, WNM, WIM, Hot Ionized Medium(HIM) (Wolfire, 2009). Hence it is very important to trace these different components and understand their dynamics, to infer the overall ISM dynamics and their influences on stellar and galactic evolution.

1.1 Different traces of galaxy elements

Different atomic and molecular components of the ISM can be traced by various spectral line emissions or absorptions that have unique wavelength signatures in the electromagnetic spectrum. The atomic hydrogen in the ISM can be seen mainly in two phases CNM and WNM, where the WNM can be traced by H I 21 cm emission line and CNM can be

traced by 21cm UV and optical absorption lines. Since the warm hydrogen atom is seen in almost the entire ISM, H I 21 cm emission line works as a good probe of large scale ISM structures. The giant molecular clouds(GMC) are gravitationally bounded density cores which are prone to instability and form the sites of a new star. They are mainly comprised of molecular hydrogen H_2 and carbon monoxide CO. Due to the lack of permanent dipole moment and rare excitation in its rotational energy levels, molecular hydrogen is difficult to detect directly (Glover and Mac Low, 2011). On the other hand, carbon monoxide emits radiation by their rotational transition at different lines (C(J=1-0) at 2.6 mm, C(J=2-1) at 1.3 mm, C(J=3-2) at 0.87 mm) which can be easily observed in millimetre wavelength range (Dickman, 1978). Hence CO is used as a proxy for molecular hydrogen and hence GMC in the ISM. The hydrogen gas that is near to the stars (mainly O and B type stars) undergoes ionization mainly by photoionization to form H II . These ionized hydrogen gases confine the hotter WIM phases of the ISM which are traced by the H_α emission at $\lambda = 6563 \text{ \AA}$. The hotter phase of the ISM, HIM is mainly heated by supernovae and is the least dense. These phases of the ISM usually go above the disc which appear as fountains or bubbles. The main traces of these gases are the absorption lines in far UV (O_{IV}) and soft X-ray emissions for much hotter phases.

Several star formations tracers have been widely used in the literature. The hot young stars are the most common star formation indicators that have been widely used (Kennicutt, 1998a). Nearby hot young stars emit far ultraviolet wavelengths ($1250 \text{ \AA} - 2500 \text{ \AA}$). This can be observed only using space based observatories like Hubble Space Telescope (HST) and Galaxy Evolution Explorer satellite (GALEX) (Maoz et al., 1996; Meurer et al., 1999). Another indicator for Star Formation Rate (SFR) is the Hydrogen recombination line at $\lambda = 6563 \text{ \AA}$ (H_α) which is caused by ionization of H I by UV radiation from young stars. Oxygen emission line [OII] ($\lambda = 3727 \text{ \AA}$) and the H_β ($\lambda = 4861 \text{ \AA}$) Hydrogen recombination line are also used as SFR tracers. The interstellar dust gets excited by the

UV radiation from the young stars which can be observed as multiple lines in the IR regions (Jarrett et al., 2012; Neugebauer et al., 1984; Werner et al., 2004). Usage of a combination of different indicators like FUV, IR, optical etc is mostly preferred to avoid limitations of individual tracers (Bigiel et al., 2008; Calzetti et al., 2007; Robert C. Kennicutt et al., 2003).

1.2 Interstellar medium at large scales

1.2.1 ISM Turbulence

In 1951 von Weizsäcker proposed a theoretical model of hierarchial formations of structures originated by turbulent motions in the ISM and hence suggests ISM is a turbulent medium. The clouds are seen in the interstellar medium which he referred as the 'eddy - element of turbulence'. They can be seen everywhere in the system in different sizes and strengths. He proposed that at a large scale, the entire galactic disc gets stirred by differential rotation and henceforth larger eddies are generated. This energy in the larger eddies is transferred over to the smaller-sized eddies and finally gets dissipated by viscosity at the smallest scale. This energy cascade can be mathematically expressed by a power law relation between the length scale and energy, like in Kolmogorov turbulence (von Weizsäcker, 1951). Observational evidence for the presence of turbulence in the ISM started to emerge when large scale correlations in H I emission (Baker, 1974), correlated structures in interstellar scintillation at subparsec scales (Little and Matheson, 1973; Rickett, 1970) were detected. Larson (1981) found that the size of molecular cloud and velocity width is related by a power law which in literature is recognized as one of the first indications of turbulence in ISM. Successively, more studies on these types of correlation in structures (Dickey, 1985; Dickey and Lockman, 1990; Dickman and Kleiner, 1985; Scalo, 1977) contributed significantly to understand the theory. Scalo (1984) and Stenholm (1984) found that CO

velocities are correlated over a range of scales. Using diagnostic tools like correlation functions, structure functions, density and velocity power spectra (detailed description in chapter 2), strong evidence for both small scale turbulence in MilkyWay (Crovisier and Dickey, 1983; Deshpande et al., 2000; Green, 1993; Roy et al., 2010, 2012) and large scale turbulence in external galaxies emerged (Begum et al., 2006; Chepurnov et al., 2015; Crovisier et al., 1985; Dutta et al., 2008, 2009; Elmegreen et al., 2001; Kauffmann et al., 2010; Maier et al., 2017; Zhang et al., 2012). Meanwhile, numerical simulations on compressible fluid turbulence were also in progress to compare these observational results and infer the generating mechanism behind ISM turbulence (Klessen, 2000; Ossenkopf and Mac Low, 2002; Padoan et al., 1999).

The driving mechanism behind this ISM turbulence has been a puzzle to the astronomers since it was first considered. From the beginning, supernovae have been claimed as one of the driving forces of turbulence that result in the generation of correlated structures being detected at scales ($\sim 100\text{pc}$) (de Avillez and Breitschwerdt, 2004; Hill et al., 2008; Joung and Mac Low, 2006; Mac Low and Klessen, 2004; Norman and Ferrara, 1996). By comparing the CO velocity dispersions of observation and simulated data, Brunt et al. (2009) conclude that supernova driven outflows generate turbulence in molecular clouds. The results of numerical simulations on MHD by Falceta-Gonçalves et al. (2010) and Ruiz et al. (2013) also suggest that stellar feedback is an important source in starburst regions and small galaxies. Even though there are numerous evidences of driving forces for small scale turbulence, whether the same driving forces are well enough to trigger large scale galactic turbulence still remains unanswered. Dutta et al. (2008) obtained the H I column density power law power spectrum of around 18 spiral galaxies where slopes are in a range of ~ -0.5 to -2.0 at large scales ranging from 1 kpc to 20 kpc. Grisdale (2017) shows through numerical simulations that the power spectrum slope of the structure which is generated in absence of supernovae feedback is -1.6 at length scales

of kiloparsec. The agreement with the results obtained by Dutta et al. (2008) indicates that supernovae may not be the possible origin behind large scale structures. Several mechanisms are proposed so far for large scale turbulence driving like galactic differential rotation, magneto-rotational instability, disc shearing, gravitational instabilities coupled with galactic rotation etc (Balbus and Hawley, 1991; de Avillez and Breitschwerdt, 2004; Fleck, 1981; Gammie et al., 1991; Joungh and Mac Low, 2006; Kim and Ostriker, 2002; Krumholz and Burkhardt, 2016; Piontek and Ostriker, 2004; Sellwood and Balbus, 1999), however with lack of measurement of the velocity power spectrum in external spiral galaxies and limited understanding of the density power spectra, the large scale ISM turbulence is yet to be understood physically.

1.2.2 Anisotropy in ISM

In addition to the turbulence generated coherent structures, the ISM is also found to have anisotropic oscillatory patterns seen locally in the galactic disc. Such structures are commonly termed vertical corrugations or bending waves. The most common patterns among them are wraps and bowl (Levine et al., 2006). In a series of discoveries, many such substructures related to bending and breathing modes have since been identified (Bennett and Bovy, 2019; Carrillo et al., 2019; Cheng et al., 2020; Gómez et al., 2012; López-Corredoira et al., 2020; Morganson et al., 2016; Price-Whelan et al., 2015; Schönrich and Dehnen, 2018; Slater et al., 2014; Wang et al., 2020, 2018; Widrow et al., 2012; Williams et al., 2013; Xu et al., 2015; Yanny and Gardner, 2013) from within the solar radius up to the edges of the stellar disc. A number of physical mechanisms have been put forward to understand the bending waves in disc galaxies, such as tidal interaction with satellites or companion galaxies (Bland-Hawthorn and Tepper-García, 2021; Bland-Hawthorn et al., 2019; Edelson and Elmegreen, 1997; Gómez et al., 2013, 2016, 2017, 2021; Grion Filho et al., 2021; Hunt et al., 2021; Hunter and Toomre, 1969; Laporte et al., 2019; Poggio et al.,

2021; Schönrich and Dehnen, 2018; Schwarzkopf and Dettmar, 2001; Weinberg, 1998; Weinberg and Blitz, 2006; Widrow et al., 2014); intergalactic matter accretion onto the dark halo (Jiang and Binney, 1999) or directly onto the disc (López-Corredoira et al., 2002); intergalactic magnetic field (Battaner et al., 1990), intergalactic wind (Kahn and Woltjer, 1959) etc. Bending waves are shown to also arise, from various internal instabilities (Araki, 1985; Chequers and Widrow, 2017; Revaz and Pfenniger, 2004; Sellwood, 1996), from resonant coupling (Binney, 1981), due to the dynamical friction between a disc and its halo (Nelson and Tremaine, 1995) and even due to the halo substructure (Chequers et al., 2018).

While direct detection of corrugation in neighbouring discs seems far-fetched and limited to near edge-on discs, several authors have looked for possible kinematic signatures (wavy undulations in mean velocity perpendicular to disc) in face-on discs (Alfaro et al., 2001; D’Onghia et al., 2016; Gómez et al., 2021; Sánchez-Gil et al., 2015) and even found them. Yet the problem is that spatial corrugation and its associated vertical velocity corrugation cannot be measured (except in Milky Way) in the same system. Therefore the observed velocity corrugation could not have been attributed unambiguously to disc bending. This issue was resolved after a series of recent simulations studying the bending wave generation and evolution in Milky Way - Sagittarius Dwarf interaction where they found that the bending waves are always associated with an oscillatory pattern in the disc’s mean vertical velocity (Bland-Hawthorn and Tepper-García, 2021; Bland-Hawthorn et al., 2019; Chequers and Widrow, 2017; Chequers et al., 2018; Gómez et al., 2013, 2016, 2017, 2021; Laporte et al., 2019; Widrow et al., 2014). These studies, also establish a quantitative connection between bending waves and vertical velocity patterns. Darling and Widrow (2019) found that a mid-plane deviation of 2 kpc could lead to a change in mean vertical velocity of about $50 - 60 \text{ km s}^{-1}$ in their simulations of the Milky Way. Antoja et al. (2018) observe a similar connection in our Galaxy where a mid-plane bend of 1 kpc corresponds to 30 km s^{-1} . Laporte et al. (2018b) note that the velocity fluctuations can vary from

almost none in the inner galaxy to $\sim 10 \text{ km s}^{-1}$ at $R = 10 \text{ kpc}$. In the outer disc, beyond the Monoceros ring, these fluctuations can reach as much as 50 km s^{-1} .

1.3 Interaction between ISM and star formation

ISM supplies all the matter required for the formation of stars. Neutral hydrogen, raw material for star formation, eventually collapses to form giant molecular clouds (GMCs) to various effects. During the different stages of a star, it emits an enormous amount of energy and matters in various ways back to ISM, which results in the enrichment of the ISM contents with heavy elements and also many complex dynamical activities like turbulence in ISM (de Blok et al., 2008). Hence the interaction between the stellar evolution and ISM are complementary.

In 1959 Schmidt formulate a simple power law relation between the density of gas in the ISM and star formation (Schmidt, 1959). This was later tested by various observational studies in many systems (Bigiel et al., 2008; Kennicutt, 1998a,b; Wong and Blitz, 2000). Kennicutt (1989) proposed a modified star formation law which applies to the galactic disc with measurable quantities such as surface density Σ . Hence modified law is called Kennicutt–Schmidt (K–S) law given as $\Sigma_{SFR} \propto \Sigma_{gas}^N$. A comprehensive study by Kennicutt (1998b) found that the power law index is $N = 1.4 \pm 0.15$ for a large range of values in SFR. Similar studies by Wong and Blitz (2002) and Bigiel et al. (2008) on several spirals and dwarfs show a tight correlation between Σ_{H_2} and SFR and most of the galaxies do not show much correlation between H I density and SFR. Brosch et al. (1998) also found an absence of correlation between H I and SFR in dwarf galaxies too. In most of these studies, when only molecular hydrogen is considered in the gas part, the index shows a value near unity (Dessauges-Zavadsky et al., 2014; Leroy et al., 2008), whereas SFR has a nonlinear power law relationship with atomic and molecular gas densities (Boissier et al., 2003; Schruba et al., 2011). Bigiel et al. (2010a) show a tight correlation between the H I

gas and far-ultraviolet (FUV) emissions, one of the SFR tracers in the outskirts of spiral galaxy M83. They also suggest that the high-density H I regions can act as the home for star formation. Bigiel et al. (2010b) also see a similar correlation with H I and SFR traces in several nearby spiral galaxies using THINGS and the GALEX Nearby Galaxy Survey. Meanwhile, observational results by Fumagalli and Gavazzi (2008); Rownd and Young (1999) show that decrease or depletion in H I results in a successive decrease in SFR, an indication that H I gas is being used up in star formation either directly or indirectly.

Stellar evolution and feedback play important roles in the entire evolution and dynamics of the ISM and also the galaxy. Commonly observed feedbacks are stellar radiations, winds, mass ejection, Supernova etc, which result in the ionization of the surrounding medium, momentum or mass transfer, shocks in the ISM etc. Aftereffect of these feedbacks is enrichment of heavier elements, redistribution of matter, structure formation, turbulent flow generations, compression to induce new sites of star formation etc (Grisdale, 2017; Shore, 1981)). At the same time, stellar feedback also includes negative effects by increasing the kinetic energy of the ISM, generating excess pressure and hence hinders star formation (Dekel and Silk, 1986; Larson, 1981; Mac Low and Klessen, 2004; Silk and Rees, 1998). Overall star formation, its feedback, its interplay with ISM and the effect of turbulence in star formation are the areas that require much attention and they need to be studied with care.

1.4 Motivation

Out of the different phases in the ISM, CNM and WNM are the most commonly observed phases. Kanekar et al. (2011) have shown that there is a column density threshold for the formation of CNM. Roy et al. (2008) demonstrated that the WNM have relatively less gas than what was classically expected. These and other observations along with several simulations of the ISM suggest that a significant fraction of the gas lies in an unstable

phase of ISM with temperature in between the CNM and WNM. Possible fuel behind the mere existence of gas in such an unstable phase can be the energy cascade from the large scale turbulence. Investigation of large scale structure and dynamics of the ISM for characteristics of turbulence can only be done with observation of ISM in external spiral galaxies. There are limited reports of such investigations in literature.

Tamburro et al. (2009) has shown that most of the spiral galaxies observed in THINGS have extraordinarily high H I velocity dispersion. The part of the velocity dispersion is most likely due to existence of turbulence in ISM at various scales. Dutta et al. (2008) found large scale coherent structure is common in external spiral galaxies with hint of compressive fluid turbulence generating them. Though there is evidence from observations and various simulations, that star formation feedback is a major source of turbulence at small scale, the apparent reason behind the large scale turbulence is still not clear. Two point statistical estimation of velocity structures in the ISM gives a direct measurement of energy input of turbulence in the ISM, however, it is practically difficult to estimate this for external spiral galaxies (Dutta, 2015). Inferences on the energy input of large scale turbulences has been carried in the Milkyway by Chepurnov et al. (2010) using the velocity coordinate spectrum (VCS) technique where they suggested the presence of shock-dominated compressible origin. Velocity Centroids, velocity channel analysis etc are some other techniques that have been suggested and used for velocity measurement in our Galaxy (Esquivel and Lazarian, 2005; Lazarian and Pogosyan, 2000, 2006; Padoan et al., 2001). However, these techniques have limitations in applying to spiral galaxies (Dutta, 2015). An alternative estimator for the column density as well as the line of sight velocity power spectrum using radio interferometric observations of H I fluctuations is proposed by Dutta (2016). As part of this thesis, we present here a variant of this method for the measurement of large scale turbulence cascade, implement the column density and line of sight velocity power spectrum and use them to investigate the turbulence origin.

Random motions generated by turbulence in the ISM regulates the star formation in two different ways. On one hand, it seeds the star formation by triggering the collapse of denser regions through fragmentation. On the other hand it also hinders star formation by introducing excess pressure to reduce the collapse. Star formation rates in the galaxies are observed too slow below the level expected from the number of gas reservoirs that are present in the ISM (Federrath, 2018). Turbulence is the possible reason for the slow rate of star formation as it throws away the gas from the clouds. Meanwhile, observational analysis of Kennicutt-Schmidt law shows the existence of a break or star formation below a critical density is low in spiral galaxies (Boissier et al., 2003; Kennicutt, 1998a; Martin and Kennicutt, 2001). Renaud et al. (2012) proposed analytically that turbulence is related to this transition where he suggests that supersonic turbulence results in the formation of shocks which could later trigger gravitational collapse. Kraljic et al. (2014) show through simulations like of Milkyway, LMC and SMC that supersonic turbulence generated by self-gravity at large scales (at the size of spiral arms) compress gas and seeds star formation. Most of the studies and observational evidence on the role of turbulence in the star formations are limited to small scale turbulence at the size of GMCs (Ballesteros-Paredes et al., 2006; Elmegreen, 2008; Federrath and Klessen, 2012; Gritschneider et al., 2009; Orkisz, Jan H. et al., 2017; Renaud et al., 2014). We would like to investigate the effect of turbulence at the passage of H I to star formation at various scales in this thesis.

The turbulent generated structures that are seen in the density and velocity field are rather coherent and scale invariant. ISM structure and dynamics also comprise local oscillatory undulations that have been seen in the Galactic disc. Simulations results show that interaction with satellite galaxies results in the bending of a disc which causes the formation of anisotropic undulations in the disc (Poggio et al., 2021). Direct observational evidence of vertical corrugations is mostly limited to edge-on galaxies using dust or $H\alpha$ emission as tracers(Fridman et al., 1998; Narayan et al., 2020). For galaxies that are

not edge-on, detection of modes in vertical velocity components can imply the presence of bending waves. This opens up a new avenue toward quantifying the depth of a tidal interaction (Grion Filho et al., 2021; Poggio et al., 2021) for a large population of inclined galaxies. We could also use this proxy method to address the pressing questions in the hitherto less explored bending wave family ($m \neq 1$) such as (i) are they as common as warps? (ii) how long are they stable? (iii) what is their impact on galaxy evolution? (iv) are there corrugations in H I disc etc.

Hence we would like to address the following main objectives of this thesis.

- Developing appropriate estimators for the measurement of density and velocity scale invariant structures in the ISM using H I as a tracer.
- Estimation of large scale coherent structures in density and velocity using observational data of a few spiral galaxies and hence understand the presence of turbulence cascade there.
- Investigating the role of turbulence in the star formation activity by doing disc instability analysis in a few spiral galaxies and understanding their role at different length scales.
- Observational evidence for the presence of bending waves or vertical corrugations in spiral galaxies with H I as a probe.

The thesis is organized as follows. In Chapter 2, we introduce H I 21 cm line as a probe for ISM study and the technique of radio interferometry. We discuss the several statistical quantities used for measuring turbulence and discuss the result of the efficacy check on various estimators. We conclude this chapter by introducing the visibility moment estimator (VME) for column density and turbulence velocity power spectrum which are further pursued.

Implementation of VME and the first measurement of large scale turbulence cascade over a large range of length scales in two spiral galaxies are discussed in detail in Chapter 3 and we present their results. The investigation of the role of turbulence in star formation activity is discussed in Chapter 4. Observational analysis for the presence of bending waves in a sample of spiral galaxies and corresponding results are discussed in Chapter 5. We conclude this thesis in Chapter 6 by summarizing and highlighting the main scientific findings of our investigations.