

# Chapter 1

## How to shed some light on galaxies?

### 1.1 Outline of the content

#### 1.1.1 Motivation behind this work

As we look into the sky, for generations mankind has been captivated by its beauty, awestruck by the spectacular (aurora, comets), and reassured by its familiarity and constancy over the centuries. The combination of improved observations and measurements, mathematics and validated theory have transformed our understanding of the objects populating our own solar system and the most distant of galaxies. In doing so the universe has grown to fill spaces and time so vast our minds cannot easily conceive them. We have discovered new entities (black holes, supernovae, jets and pulsars, etc) that have been so vast or alien, that they are a challenge to describe. To do so has required combining theories about the very large (general relativity) and the very small (bosons, cosmic rays, quantum mechanics, etc). Hence, in contrast to the constant and familiar, astronomy and astrophysics have instead continually challenged our preconceptions and uncovered shocking and surprising discoveries.

In more recent years it has even become possible to visit space and to devise machines that enable us to peer further into space, and also to view the universe in wavelengths invisible to the human eye, the radio spectrum, x-rays, infrared, etc. The rate of discovery and understanding has accelerated. It has become apparent that magnetic fields are ubiquitous, with many planets and stars generating their own magnetic fields. Of interest to this study, it has also been discovered that the tenuous gas between the stars is magnetized and in many galaxies, including our own, these magnetic fields are organized on a galactic scale. Scientific controversy surrounds these structures, which cannot easily be explained with what we know so far about magnetism.

Despite all the advances in technology, even with instruments in orbit, observational data is effectively constrained to line of site measurements. On galactic time scales, we are also in effect viewing a freeze frame of the sky, and any understanding of motion and evolution has to be inferred by comparing differences between galaxies at different

stages of development. Assumptions and estimates must be invoked about the composition and distribution of the gas along these lines of measurement. If we can accurately model astrophysical objects in three dimensions with numerical simulations, these can be used to assess the best methods of estimating the 3D composition. The movement and structure of the astrophysical models can be investigated more easily and inexpensively than the galaxies directly, and be used to motivate useful and effective targets for future observations and investigation.

### **1.1.2 Structure and contents**

In the rest of the Introduction, I provide a brief description of galaxy structure, some of the primary mysteries of interest here and how this research might address these. Section 2 reviews some of the progress made to date with similar models and discusses the significant differences between what is and is not included within the various models.

The most substantial result of my research has been the construction of a robust and versatile numerical model capable of simulating a 3D section of a spiral galaxy. The system is extremely complicated physically and also, inevitably, numerically. The simulations need to evolve over weeks or months and overcoming numerical problems has taken a large proportion of my research time. However the most interesting outcomes are not numerical, but the results and analysis obtained from the simulations. I therefore reserve my comments on some of the critical numerical insights to the Appendices. These may be of interest to others interested in numerical modelling, but less so to the wider scientific community. However, I think it is important not to brush these issues under the carpet for at least two reasons. First, it is important to be clear and honest about the deficits in one's model, so that the reader may be able to understand how robustly the model may capture various features of the interstellar medium. Secondly, sharing the experiences may help to improve the models of others.

However, so that the reader may reasonably understand the outcomes, in Part II I fully describe the model. I state what physical components are included, and discuss the implications of any necessary numerical limitations or exclusions. In Parts III–V I describe and explain in detail the new results I have obtained. These include data from two sets of simulations, conducted over a period exceeding 12 months. They differ in that the second set include the addition of a seed magnetic field. Rather than discuss each simulation or set separately, I describe various characteristics of the ISM and consider to what extent these depend on any model parameters. Part VI contains a summary of my work, conclusions and discussion of the future of this research approach.

### **Collaborative and previously available content**

Some of the work presented in this thesis is the result of collaboration, which has been submitted for publication. A review of previous related numerical work has appeared in

a published chapter (Gent, 2012), which will form part of a book from the International Space Science Institute (ISSI). Chapter 2 covers similar subject matter, but has been substantially revised. The thesis contains material, submitted to MNRAS (Gent, Shukurov, Sarson, Fletcher and Mantere, 2013; Gent, Shukurov, Fletcher, Sarson and Mantere, 2013), in which I am lead author with co-authors Prof. A. Shukurov, Dr. A. Fletcher, Dr. G. R. Sarson and Dr. M. Mantere. The latter article forms the basis of Chapter 8, with some additional new work in Section 8.3. Material from the former article is included in Chapters 3, 5 and 6, plus Sections 7.1 and 10.1, and Appendices A and B. All numerical simulation code refinement, testing and running was performed by myself.

## 1.2 A brief description of galaxies

The largest dynamically bound structures in the universe so far observed are galaxy clusters. These collections of multiple galaxies of various types interact gravitationally and also contain an intergalactic magnetic field among other features. They occupy regions of space spanning order of 10 – 100 mega-parsecs (Mpc). Within clusters galaxies may collide, merge or accrete material from one to another. Groups of galaxies, typically spanning order 1 Mpc, contain a few dozen gravitationally bound galaxies. Our own galaxy, the Milky Way, belongs to the Local Group containing about 40 galaxies. We refer to the Galaxy (capitalised), to denote the Milky Way, to distinguish it from galaxies in general (lower case).

### 1.2.1 Classification

The next largest category in the hierarchy of such structures are the galaxies. All galaxies will interact with the intergalactic material surrounding them to a greater or lesser extent. Nevertheless they generally contain powerful internal forces and structure, which may govern the internal dynamics irrespective of the external environment. An early attempt to identify the different categories of galaxies was made by Edwin Hubble in the 1920s, illustrated in Fig. 1.1.

The classification of galaxies turned out to be more complicated than Hubble could have envisaged. In the Hubble classification galaxies are elliptical (E) or spiral (S). Spirals also include barred galaxies where the spiral arms emerge from the tips of an elongated central layer, rather than the central bulge. It may not always be certain whether a galaxy, which appears elliptical as viewed from our solar system, is not in fact a spiral, viewed face on. Subsequently van den Bergh (1976) revised Hubble’s morphological classification of galaxies, but more recently Cappellari et al. (2011), using the ATLAS<sup>3D</sup> astronomical survey, proposed a more physical classification based on the kinematic properties of galaxies. Their revised classification diagram is shown in Fig. 1.2.

Considering the kinematic properties of the galaxies improves the consistency of classification and reduces the reliance for identification on our viewing angle. It also helps

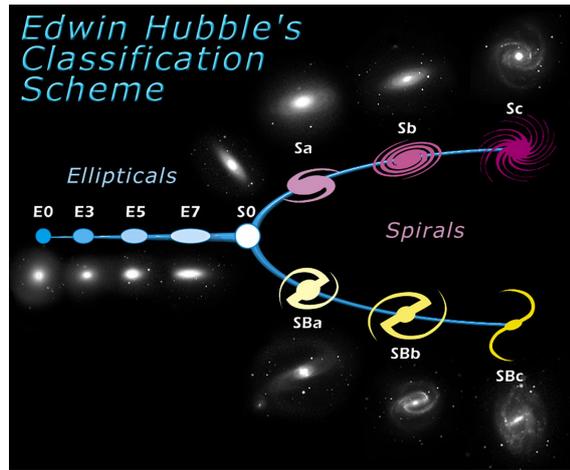


Figure 1.1: Hubble's traditional tuning fork classification diagram for galaxies. Courtesy of the European Space Agency (ESA) <http://www.spacetelescope.org/images/heic9902o/> Galaxies are defined as elliptical (E) or spiral (s) with further division of spirals into normal or barred (Sb)

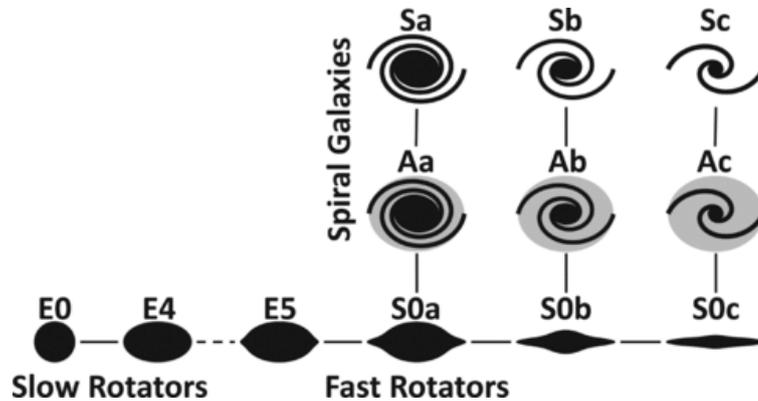


Figure 1.2: The revised galaxy classification diagram of Cappellari et al. (2011) using the ATLAS<sup>3D</sup> astronomical survey. Galaxies are categorized as slow rotators, corresponding to elliptical shapes and fast rotators, which become increasingly flattened with smaller central bulge as a result of higher angular momentum.

us to understand the underlying cause for the variation in morphology. Disc galaxies rotate faster and, significantly, about a single axis of rotation. In some cases elliptical galaxies exhibit very weak rotation. In others the shape is the result of multiple axes of rotation, with angular momentum acting in two or three transverse directions. This action counteracts the tendency to flatten perpendicular to an axis of rotation.

Cappellari et al. (2011) found only a very small proportion of galaxies are actually elliptical (about 4% in most clusters) and the rate of rotation as well as stellar density is very important to the morphology the strength of the magnetic field. It is my long term aim to model the ISM in any class of galaxy, although the current model is constructed to simulate spiral galaxies. The most comprehensive data pertains to the Galaxy, so as a first iteration with which we can verify the relevance of the model, it is convenient to use parameters matching the Galaxy in the solar neighbourhood and compare the outcomes

with what we understand of the real Galaxy.

The Galaxy is estimated to have a stellar disc of radius approximately 16 kiloparsecs (kpc) with atomic hydrogen HI up to 40 kpc, and the Sun, is estimated to be 7 – 9 kpc from the Galactic centre. (Here capitalised Sun denotes our own star.) Most of the mass in the Galaxy is in the form of non-interacting dark matter and stars, with stars accounting for about 90% of the visible mass with gas and dust the other 10%. There is a large central bulge and although hard to identify from our position inside the Galaxy, it is likely that we live in a barred galaxy. Away from the centre most of the mass is contained within a thin disc  $\pm 200$  parsecs (pc) of the mid-plane (Kulkarni and Heiles, 1987; Clemens, Sanders and Scoville, 1988; Bronfman et al., 1988; Ferrière, 2001) over a Galactocentric radius of about 4 – 12 kpc. Either side of the disc is a region referred to as the galactic halo with height of order 10 kpc. Halo gas is generally more diffuse and hotter gas in the disc.

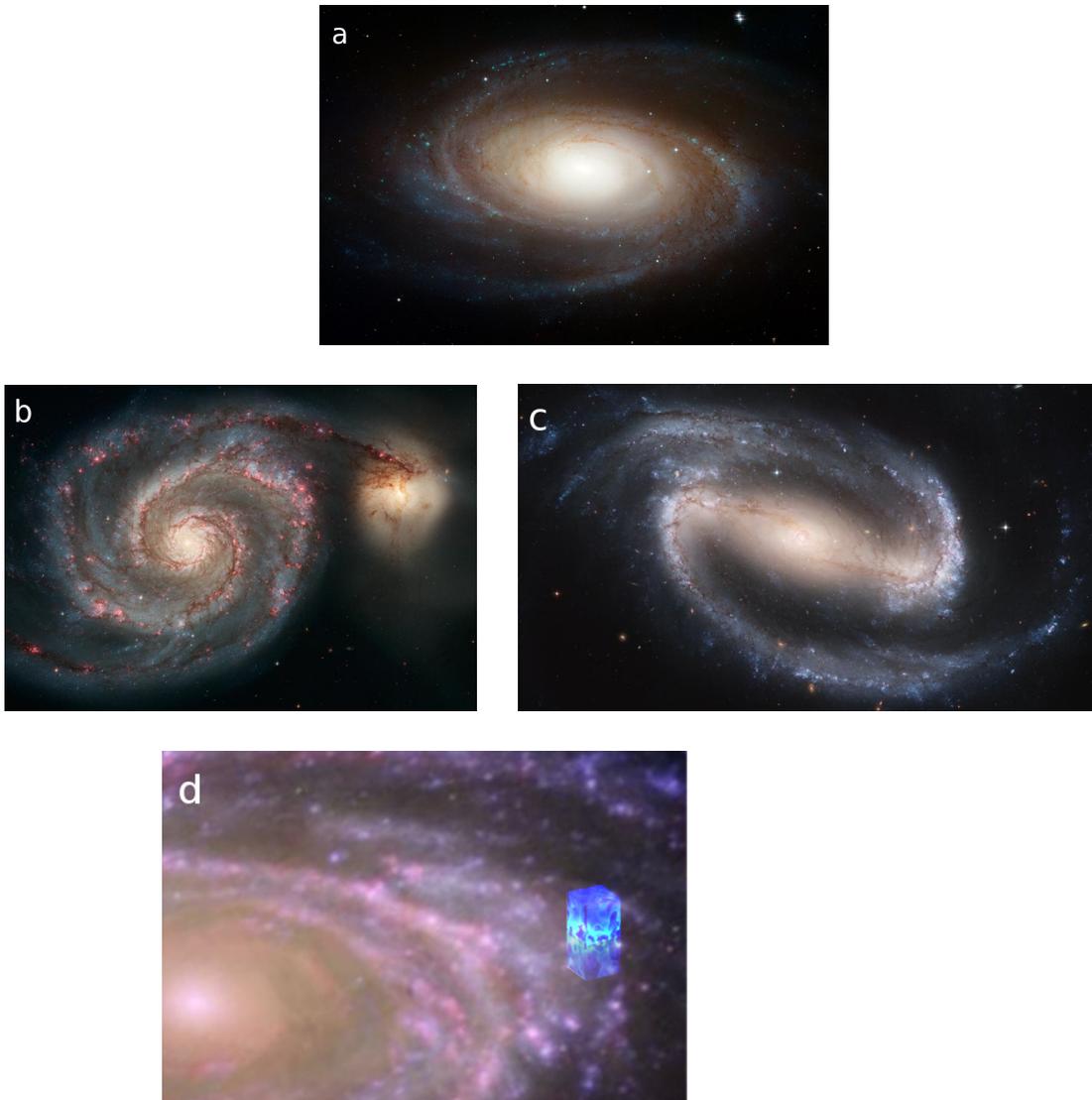


Figure 1.3: Images of spiral galaxies M81 (a), Whirlpool (b), and the barred spiral galaxy NGC 1300 (c) from <http://hubblesite.org/gallery/album/galaxy/> The image in panel (d) represents the typical location of the simulation region, superimposed as a blue box, orbiting the galaxy within the mid-plane of the disc. It extends above and below the mid-plane.

Figure 1.3 shows examples of disc galaxies, in panels (a – c). Panel d indicates the typical location and size of the simulation region in a galaxy, which will be described in Part II. Here the disc is rotating around the axis at about  $230 \text{ km s}^{-1}$  (for the Galaxy in the solar neighbourhood). As the ISM nearer to the centre of a galaxy travels a shorter orbit, differential rotation induces a shear through the ISM in the azimuthal direction, with the ISM trailing further away from the galactic centre. Rotation and shear vary between different galaxies, and also over different radii within each galaxy. These features can affect the classification of a galaxy and appear to be important to the strength and organization of the magnetic field.

## 1.2.2 The interstellar medium

The space between the stars is filled with a tenuous gas, the interstellar medium (ISM), which is mainly hydrogen (90.8% by number [70.4% by mass]) and helium (9.1% [28.1%]), with much smaller amounts of heavier elements also present and a very small proportion of the hydrogen in molecular form (Ferrière, 2001). The density of the ISM in the thin disc is on average below  $1 \text{ atom cm}^{-3}$ . (In air at sea level the gas number density is about  $10^{27} \text{ cm}^{-3}$ .) The ISM contains gas with a huge range in density and temperature, and can be described as a set of phases each with distinct characteristics.

The multi-phase nature of the ISM affects all of its properties, including its evolution, star formation rate, galactic winds and fountains, and behaviour of the magnetic fields, which in turn feed back into the cosmic rays. In a widely accepted picture (Cox and Smith, 1974; McKee and Ostriker, 1977), most of the volume is occupied by the hot ( $T \simeq 10^6 \text{ K}$ ), warm ( $T \simeq 10^4 \text{ K}$ ) and cold ( $T \simeq 10^2 \text{ K}$ ) phases. The concept of the multi-phase ISM in pressure equilibrium has endured with modest refinement (Cox, 2005). Perturbed cold gas is quick to return to equilibrium due to short cooling times, while warm diffuse gas with longer cooling times has persistent transient states significantly out of thermal pressure balance (Kalberla and Kerp, 2009, and references therein). Dense molecular clouds, while containing most of the total mass of the interstellar gas, occupy a negligible fraction of the total volume and are of key importance for star formation (e.g. Kulkarni and Heiles, 1987, 1988; Spitzer, 1990; McKee, 1995). Gas that does not form one of the three main, stable phases but is in a transient state, may also be important in some processes. The main sources of energy maintaining this complex structure are supernova explosions (SNe) and stellar winds (Mac Low and Klessen, 2004, and references therein). The clustering of SNe in OB associations facilitates the escape of the hot gas into the halo thus reducing the volume filling factor of the hot gas in the disc, perhaps down to 10% at the mid-plane (Norman and Ikeuchi, 1989). The energy injected by the SNe not only produces the hot gas but also drives compressible turbulence in all phases, as well as driving outflows from the disc associated with the galactic wind or fountain, as first suggested by Bregman (1980). Thus turbulence, the multi-phase structure, and the disc-halo connection are intrinsically related features of the ISM.

Although accounting for only about 10% of the total visible mass in galaxies, the turbulent ISM is nevertheless important to their dynamics and structure. Heavy elements are forged by successive generations of stars. These are recycled into the ISM by SN feedback and transported by the ISM around the galaxy to form new stars. The ISM supports the amplification and regulation of a magnetic field, which also affects the movement of gas and subsequent location of new stars. Heating and shock waves within the ISM, primarily driven by supernovae, results in thermal and turbulent pressure alongside magnetic and cosmic ray pressure, which supports the disc against gravitational collapse.

# Chapter 2

## A brief review of interstellar modelling

### 2.1 Introduction

Work to produce a comprehensive description of the complex dynamics of the multi-phase ISM has been significantly advanced by numerical simulations in the last three decades, starting with Chiang and Prendergast (1985), followed by many others including Rosen, Bregman and Norman (1993); Rosen and Bregman (1995); Vázquez-Semadeni, Passot and Pouquet (1995); Passot, Vázquez-Semadeni and Pouquet (1995); Rosen, Bregman and Kelson (1996); Korpi, Brandenburg, Shukurov, Tuominen and Nordlund (1999); Gazol-Patiño and Passot (1999); Wada and Norman (1999); de Avillez (2000); Wada and Norman (2001); de Avillez and Berry (2001); de Avillez and Mac Low (2002); Wada, Meurer and Norman (2002); de Avillez and Breitschwerdt (2004); Balsara et al. (2004); de Avillez and Breitschwerdt (2005*a,b*); Slyz et al. (2005); Mac Low et al. (2005); Joung and Mac Low (2006); de Avillez and Breitschwerdt (2007); Wada and Norman (2007); Gressel et al. (2008*a*); Hill et al. (2012).

Numerical simulations of this type are demanding even with the best computers and numerical methods available. The self-regulation cycle of the ISM includes physical processes spanning enormous ranges of gas temperature and density, as well as requiring a broad range of spatial and temporal scales. It involves star formation in the cores of molecular clouds, assisted by gravitational and thermal instabilities at larger scales, which evolve against the global background of transonic turbulence, in turn, driven by star formation and subsequent SNe (Mac Low and Klessen, 2004). It is understandable that none of the existing numerical models cover the whole range of parameters, scales and physical processes known to be important.

Two major approaches in earlier work focus either on the dynamics of diffuse gas or on dense molecular clouds. In this chapter I will review a range of previous and current models, relating them to the physical features they include or omit. As with the general structure of the thesis, it is the extent to which physical processes are investigated that is of most interest, therefore I shall consider the physical problems and detail how various numerical approaches have been applied to these.

## 2.2 Star formation and condensation of molecular clouds

I shall not explicitly consider star formation. This occurs in the most dense clouds, which form from compressions in the turbulent ISM. As densities and temperatures attain critical levels in the clouds the effects of self-gravity and thermal instability may accelerate the collapse of regions within the clouds to form massive objects, which eventually ignite under high pressures to form stars.

The clouds themselves typically occupy regions spanning only a few parsecs. The final stages of star formation occurs on scales many magnitudes smaller than that, which may be regarded as infinitesimal by comparison to the dynamics of the galactic rotation and disc-halo interaction. Bonnell et al. (2006) model star formation by identifying regions of self gravitating gas of number density above  $10^5 \text{ cm}^{-3}$  and size  $\leq 0.5 \text{ pc}$ . To track the evolution of even one star, requires very powerful computing facilities, and a time resolution well below 1 year. Currently this excludes the possibility of simultaneously modelling larger scale interstellar dynamics.

Modelling on the scale of molecular clouds, incorporating subsonic and supersonic turbulence and self-gravity is reported in Klessen, Heitsch and Mac Low (2000) and Heitsch, Mac Low and Klessen (2001) with and without magnetic field. These authors investigated the effect of various regimes of turbulence on the formation of multiple high density regions, which may then be expected to form stars. The subsequent collapse into stars was beyond the resolution of these models. Magnetic tension inhibited star formation, but this was subordinate to the effect of supersonic turbulence, which enhanced the clustering of gas within the clouds. These clusters provide the seed for star formation. In these models, supersonic turbulence was imposed by a numerical prescription. Physically the primary drivers of turbulence are SNe, and these evolve on scales significantly larger than the computational domain, so it would be difficult to include SNe and the fine structure of molecular clouds in the same model.

In addition to compression and self-gravity, thermal instability may also accelerate the formation of high density structures within the ISM. Brandenburg, Korpi and Mee (2007) investigated the effects of turbulence and thermal instability, including scales below 1 pc. Their analysis concluded that turbulent compression dominated that of thermal instability in the formation of the densest regions. The minimum cooling times were far longer than the typical turnover time of the turbulence.

Slyz et al. (2005) included star formation and a thermally unstable cooling function with a numerical domain spanning 1.28 kpc. The typical resolution was 10 or 20 pc. As previously stated, the dynamics of compression at higher resolution substantially dominate those of self-gravity and thermal instability. At this resolution, maximum density was about  $10^2 \text{ cm}^{-3}$  and minimum temperatures were above 300. They found a sensitivity in their results to the inclusion or exclusion of self-gravity, which Heitsch, Mac Low and Klessen (2001), with higher resolution, found to be subordinate to the effects of turbulence on the density profile. I would argue that this indicates that including self-gravity at

such large scales may therefore produce artificial numerical rather than physical effects. The gravitational effect of the ISM on scales greater than 1 pc are negligible, compared to stellar gravity and other dynamical effects.

In summary, modelling star formation and molecular clouds in the ISM necessitates a resolution significantly less than 1 pc. Self-gravity within the ISM is significant only for dense structures inside molecular clouds. Such gravitation is proportional to  $l^{-2}$ , where  $l$  denotes the distance from some mass sink, so is a highly localised phenomenon. Star formation in large scale modelling can therefore at best be parametrized by the removal of mass from the ISM based on the distribution of dense mass structures and self-gravity neglected.

## 2.3 Discs and spiral arms

To model a whole spiral galaxy requires a domain radius of order 10 kpc and potentially double that in height to include the halo. Often to avoid excessive computation, when modelling scales spanning the whole disc some authors either adopt a 2D horizontal approach (Slyz, Kranz and Rix, 2003), or adopt a very low vertical extent in 3D (Dobbs and Price, 2008; Hanasz, Wóltański and Kowalik, 2009; Kulesza-Żydzik et al., 2009; Dobbs and Pringle, 2010). Given the mass, energy and turbulence are predominantly located within a few hundred parsecs of the mid-plane, some progress can be made with this approach.

A number of important physical features of the ISM must be neglected at this resolution. An important factor in the self-regulation of the ISM is the galactic fountain, in which over-pressured hot gas in the disc is convected into the halo, where it cools and rains back to the disc. How this affects star-formation and SNe rates is poorly understood.

The multi-phase ISM cannot currently be resolved at these scales. The cold diffuse gas exists in clumpy patches of at most a few parsecs. Even the hot bubbles of gas, generated at the disc by SNe and clusters of SNe are typically less than a few hundred parsecs across. The resolution of these global models is of order 100 pc, which is insufficient to include the separation of scales of about  $10^3$  between the hot and the warm gas. Generally these models apply an isothermal ISM. Dobbs and Price (2008) include a multiphase medium, by defining cold and warm particles, with fixed temperature and density, but must exclude any interaction between the phases.

The random turbulence driven by SNe must also be neglected or weakly parametrized. Dobbs and Price (2008) exclude SNe with the effect of significantly reducing the disc height between the spiral arms. Hanasz, Wóltański and Kowalik (2009) neglect the thermal and kinetic energy and inject energy only through current rings of radius 50 pc and 1% of the total SN energy. Slyz, Kranz and Rix (2003) use forced supersonic random turbulence to generate density perturbations.

These models can reproduce structures similar to spiral arms and, where a magnetic

field is included, an ordered field on the scale of the spiral arms. These can be related to different rates of rotation and for various density profiles. Even in 3D however these only describe the flat 2D structure of the disc and spiral arms. Both the velocity and the magnetic fields are vectors and subject to non-trivial transverse effects. The effect of asymmetry on these vectors in the vertical direction cannot be well represented with this geometry.

Features such as the vertical density distribution of the ISM, the thermal properties and turbulent velocities cannot be understood from these models. They must be introduced as model parameters, derived from observational measurements or smaller scale simulations. On the other hand structures such as spiral arms are too large to generate in more localised simulations. The global simulations may help to identify suitable parameters for introducing spiral arms into local models, such as the scale of the density fluctuations, orientation of the arms, typical width of the arms, how the strength or orientation of the magnetic field varies between the arm and interarm regions.

## **2.4 The multi-SNe environment**

This thesis concerns modelling the ISM in a domain larger than the size of molecular clouds (Sect 2.2) and much smaller than a galaxy, or even just the disc (Sect 2.3). Models on this scale were introduced by Rosen, Bregman and Norman (1993), in 2D with much lower resolution, and without SNe. Nonetheless these already were able to identify features of the galactic fountain and the multiphase structure of the ISM. Individual SNe were investigated numerically by Cowie, McKee and Ostriker (1981). Extensive high resolution simulations led to the refinement of the classic Sedov-Taylor solution (Sedov, 1959; Taylor, 1950) and subsequent snowplough describing the evolution of an expanding blast wave (Ostriker and McKee, 1988; Cioffi, McKee and Bertschinger, 1998). The modelling of multiple SNe in the form of superbubbles within a stratified ISM was advanced by Tomisaka (1998). The first 3D simulations of SNe driven turbulence in the ISM were by Korpi, Brandenburg, Shukurov, Tuominen and Nordlund (1999) and, independently, de Avezil (2000). In this section I consider the key physical and numerical elements of these and subsequent similar models, and the extent to which their inclusion or omission improves or hinders the results.

### **2.4.1 The stratified interstellar medium**

From the images in Fig.1.3 and the profiles illustrated in Fig. 1.2 it can be seen that the matter in spiral galaxies is substantially flattened into a disc. This morphology strongly depends on the rate and form of rotation of the galaxy. Towards the centre of these galaxies is a bulge, where the density structure and dynamics differ substantially from those in the disc. In elliptical galaxies the structure may involve asymmetries that are complicated to model. I shall defer consideration of the central region and elliptical galaxies to

elsewhere and confine this thesis to the investigation of the disc region of fast rotating galaxies.

Along the extended plane of the disc in fast rotators the dense region of gas may reasonably be approximated as unstratified to within about a few hundred parsecs of the mid-plane depending on the galaxy. The thickness of the disc away from the central bulge can, in many cases, to first approximation be regarded as constant, although it does usually increase exponentially away from the galactic centre. Thus, towards the outer galaxy, even over relatively short distances the flat disc approximation breaks down. Providing the model domain remains sufficiently within the thickness of the disc, some progress can be made by ignoring stratification, (eg Balsara et al., 2004; Balsara and Kim, 2005).

Important to the dynamics of the interstellar medium is its separation into characteristic phases in apparent pressure equilibrium. Is this separation a real physical effect, or just a statistical noise? What are the thermodynamical properties of the gas, what are the filling factors, typical motions and, if the phases do in fact differ qualitatively, how do they interact? The answers to these questions are critically different when considering the ISM to be stratified or not. Balsara et al. (2004) investigated the effect of increasing rates of supernovae on the composition of the ISM. With initial density set to match the mid-plane of the Galaxy, increasing the rate of energy injection resulted in increased proportions of cold dense and hot diffuse gas and correspondingly less warm gas. The typical radius of SN remnant shells in such a dense medium remained below 50 pc before being absorbed into the surrounding turbulence. The result of increased SNe is higher pressures and eventually overheating of the ISM.

However when a stratified ISM is included, the increased pressure from SNe near the mid-plane is released away from the disc, by a combination of diffuse convection and blow outs of hot high pressure bubbles. Korpi, Brandenburg, Shukurov and Tuominen (1999); de Avillez (2000); de Avillez and Berry (2001) included stratification. They found superbubbles, which combine multiple SNe merging or exploding inside existing remnants in the disc and then breaking out into the more diffuse layers, where they transport the hot gas away. They also had individual SNe exploding at distances  $\gtrsim 500$  pc from the mid-plane, where the ambient ISM is very diffuse and the remnants of these SNe extend to a radius of a few hundred parsecs. This also has an effect on the typical pressures, turbulent velocities and mixing scales. Instead of the cold gas and hot gas becoming more abundant at the mid-plane, the hot gas is transported away and the thickness of the disc expands reducing the mean density and mean temperature at the mid-plane.

Due to the gravitational potential, dominated by stellar mass near the mid-plane, there is a vertical density and pressure gradient. This will vary depending on the galaxy, but in most simulations of this nature it is useful to adopt the local parameters, since data relating to the solar neighbourhood is generally better understood, and therefore is convenient for benchmarking the results of numerical simulations.

There is a natural tendency for cold dense gas to be attracted to the mid-plane and

hot diffuse gas to rise and cool. Estimates from observations in the solar vicinity place the Gaussian scale height of the cold molecular gas at about 80 pc and the neutral atomic hydrogen about 180 pc (Ferrière, 2001). The warm gas is estimated to have an exponential scale height of 390 – 1000 pc. Observationally hot gas is more difficult to isolate and estimates vary for the exponential scale height; ranging from as low as 1 kpc to over 5 kpc. Hence to reasonably produce the interaction between the cold and warm gas, we at least need to extend  $\pm 1$  kpc vertically. de Avillez (2000) with a vertical extent of  $\pm 4$  kpc found the ISM above about 2.5 kpc to be 100% comprised of hot gas, and this vertical extent was not high enough to observe the cooling and recycling of the hot gas back to the disc. Subsequent models (including de Avillez and Mac Low, 2001; de Avillez and Berry, 2001; de Avillez and Mac Low, 2002; Joung and Mac Low, 2006; Joung, Mac Low and Bryan, 2009; Hill et al., 2012) use an extended range in  $z$  of  $\pm 10$  kpc and find the volume above about  $\pm 2.5$  kpc almost exclusively occupied by the hot gas for column densities and SNe rates comparable to the solar vicinity. Many of these models exclude the magnetic field and all exclude cosmic rays so the models have somewhat thinner discs than expected from observations. With the inclusion of magnetic and cosmic ray pressure, we expect the disc to be somewhat thicker and the scale height of the hot gas to increase.

The build up of thermal and turbulent pressure by SNe near the mid-plane generates strong vertical flows of the hot gas towards the halo. With vertical domain  $|z| = 10$  kpc de Avillez and Breitschwerdt (2004) are able to attain an equilibrium with hot gas cooling sufficiently to be recycled back to the mid-plane, replenishing the star forming regions and subsequently SNe. Such recycling may be expected to occur in the form of a galactic fountain. However Korpi, Brandenburg, Shukurov and Tuominen (1999); Korpi, Brandenburg, Shukurov, Tuominen and Nordlund (1999) found the correlation scale in the warm gas of the velocity field remained quite consistently about 30 pc independent of  $z$  location, but in the hot gas it increased from about 20 pc at the mid-plane to over 150 pc at  $|z| \simeq 300$  pc and increasing with height. Other authors report correlation scales similar near the mid-plane, but the vertical dependence of correlation lengths requires further investigation. If there is an increase in the correlation length of the velocity field with height, as  $|z| \rightarrow 1$  kpc the scale of the turbulent structures of the ISM can become comparable to the typical size of the numerical domain. Consequently in extending the  $z$ -range to include the vertical dimension of the hot gas, its horizontal extent may exceed the width of too narrow a numerical box. With a vertical extent of only  $\pm 1$  kpc, or with Gressel et al. (2008a)  $\pm 2$  kpc, there is a net outflow of gas. Without a mechanism for recycling the hot gas, net losses eventually exhaust the disc and the model parameters cease to be useful. Korpi, Brandenburg, Shukurov, Tuominen and Nordlund (1999) found this restriction limited the useful time frame to a few hundred Myr. It is difficult to combine in one model the detailed dynamics of the SNe driven turbulence about the mid-plane with a realistic global mechanism for the recycling of the hot gas.

There has also been some discussion on the effect of magnetic tension inhibiting these

outflows. Using 3D simulations of a stratified but non-turbulent ISM with a purely horizontal magnetic field Tomisaka (1998) placed an upper bound on this confinement. When the ISM is turbulent the magnetic field becomes disordered, the ISM contains pockets of diffuse gas, and the opportunity for hot gas blow outs increases substantially (see e.g. Korpi, Brandenburg, Shukurov and Tuominen, 1999; de Avezil and Breitschwerdt, 2004, 2005b).

### 2.4.2 Compressible flows and shock handling

The ISM is highly compressible, with much of the gas moving at supersonic velocities. The most powerful shocks are driven by SNe. Accurate modelling of a single SNe in 3D requires high resolution and short time steps (Ostriker and McKee, 1988). On the scales of interest here, hundreds or thousands of SNe are required and this constrains the time and resolution available to model the SNe. Approximations need to be made, which retain the essential characteristics of the blast waves and structure of the remnants at the minimum physical scales resolved by the model.

Shock handling is optimised (by e.g. de Avezil, 2000; Balsara et al., 2004; Mac Low and Klessen, 2004; Joungh and Mac Low, 2006; Gressel et al., 2008a) through adaptive mesh refinement (AMR), where increased resolution is applied locally for regions containing the strongest contrasts in density, temperature or flow. With increased spatial resolution the time step must also be much smaller, so there are considerable computational overheads to the procedure. Many of the codes utilising AMR do not currently include modelling of differential rotation, although Gressel et al. (2008a) does apply shear using the Nirvana<sup>1</sup> code. An alternative approach is to apply enhanced viscosities where there are strong convergent flows (by e.g. Korpi, Brandenburg, Shukurov, Tuominen and Nordlund, 1999). This broadens the shock profiles and removes discontinuities, so care needs to be taken that essential physical properties are not compromised.

### 2.4.3 Distribution and modelling of SNe

There are a number of different types of supernovae, with different properties and origin. Type Ia SNe arise from white dwarfs, which are older stars that have used up most of their hydrogen and comprise mainly of heavier elements oxygen and carbon. If, through accretion or other mechanisms, their mass exceeds the Chandrasekhar limit (Chandrasekhar, 1931) of approximately  $1.38M_{\odot}$  they become unstable and explode. Type Ia are observed in all categories of galaxy and can have locations isolated from other types of SNe.

Type II SNe are produced by massive, typically more than  $10M_{\odot}$ , relatively young hot stars, which rapidly exhaust their fuel and collapse under their own gravity before exploding. Type Ib and Ic are characterized by the absence of hydrogen lines in their spectrum and, for Ic, also their helium, which has been stripped by either stellar winds

<sup>1</sup><http://nirvana-code.aip.de/>

or accretion, before the more dense residual elements collapse to form SNe. Otherwise Type II, Ib and Ic SNe are very similar, located only in fast rotating galaxies and populating mainly the star forming dense gas clouds near the mid-plane of the disc. For the remainder of this thesis I shall collectively denote these as Type CC (core collapsing) and Type I shall refer only to Type Ia. Type CC SNe are more strongly correlated in space and time than Type I, because they form in clusters, evolve over a few million years and explode in rapid succession.

In many disc galaxies, including the Milky Way, Type CC SNe are much more prolific than Type I. Both types effectively inject  $10^{51}$  erg into the ISM (equivalent to  $10^{40}$  modern thermo-nuclear warheads exploded simultaneously). Type CC also contribute  $4 - 20 M_{\odot}$  as ejecta at supersonic speeds of a few thousand  $\text{km s}^{-1}$ . Mainly located in the most dense region of the disc, Type CC SNe energy can be more rapidly absorbed and explosion sites reach a radius of typically 50 pc before becoming subsonic, while some Type I explode in more diffuse gas away from the mid-plane and can expand to a radius of a few hundred parsecs. Because Type CC are correlated in location and time, many explode into or close to existing remnants and form superbubbles of hot gas, which help to break up the dense gas shells of SN remnants and increase the turbulence. Heating outside the mid-plane by Type I SNe helps to disrupt the thick disc and increase the circulation of gas from within.

A common prescription for location of SNe in numerical models, is to locate them randomly, but uniformly in the horizontal plane and to apply a Gaussian or exponential random probability distribution in the vertical direction, with its peak at the mid-plane  $z = 0$ . Having determined the location, an explosion is then modelled by injecting a roughly spherical region containing mass, energy and/or a divergent velocity profile. The sphere needs to be large enough, that for the given resolution, the resulting thermal and velocity gradients are numerically resolved. This means that for typical resolution of a few pc the radius of the injection site will be several parsecs and indicative of the late Sedov-Taylor or early snowplough phase (See Section 3.2 and Appendix A.1) some thousands of years after the explosion. Subsequently gas is expelled by thermal pressure or kinetic energy from the interior to form an expanding supersonic shell, which drives turbulent motions and heats up the ambient ISM. Problems have been encountered with modelling the subsequent evolution of these remnants. Cooling can dissipate the energy before the remnant shell is formed. Using kinetic rather than thermal energy to drive the SNe evolution is hampered by the lack of resolution.

As well as being physically consistent, clustering of SNe mitigate against energy losses by ensuring they explode in the more diffuse, hot gas where they are subject to lower radiative losses. To achieve clustering for the Type CC SNe Korpi, Brandenburg, Shukurov and Tuominen (1999) selected sites with a random exponential distribution in  $z$ , excluded sites in the horizontal plane with density below average for the layer and then applied uniform random selection. de Avillez (2000) apply a more rigorous prescription to locate 60% of Type CC in superbubbles, in line with observational estimates (Cowie,

Songaila and York, 1979). In addition to a simplified clustering scheme Joung and Mac Low (2006) and Joung, Mac Low and Bryan (2009) also adjust the radii of their SNe injection sites to enclose  $60M_{\odot}$  of ambient gas. This appears to optimise the efficiency of the SNe modelling; avoiding high energy losses at  $T > 10^8$  K with a smaller injection site or avoiding too large an injection site, which dissipates the energy before the snowplough phase can be properly reproduced.

The critical features of the SNe modelling must ensure that the SNe are sufficiently energetic and robust to stir and heat the ambient ISM. It is unlikely that the individual remnants can be accurate in every detail, given the constraints on time and space resolution, but the growth of the remnants should be physically consistent, producing remnants and bubbles of multiple remnants at the appropriate scale. In particular we can expect about 10% of the energy to be output into the ISM in the form of kinetic energy when the remnant merges with the ambient ISM. Spitzer (1978) estimates this to be 3% and Dyson and Williams (1997) to be 30%.

#### 2.4.4 Solid body and differential rotation

To understand the density and temperature composition of the ISM the inclusion of the rotation of the galaxy is not essential. Even an appreciation of the characteristic velocities and Mach numbers associated with the regions of varying density or temperature can be obtained without rotation. Balsara et al. (2004); Balsara and Kim (2005); Mac Low et al. (2005) and de Aveliz and Breitschwerdt (2005a) investigate the magnetic field in the ISM without rotation or shear, the latter in the vertically extended stratified ISM, otherwise in an unstratified  $(200 \text{ pc})^3$  section. The latter two models impose a uniform  $\mathbf{B}$  of between  $2 - 5 \mu\text{G}$ . The turbulence breaks up the ordered field (mean denoted  $\mathbf{B}_0$ ) and with modest amplification of the total magnitude  $B$ , although the simulations last only a few hundred Myr. Over a longer period, it would be expected that  $\mathbf{B}_0$  would continue to dissipate in the absence of any restoring mechanism (rotation). They analyze the distribution with respect to density and temperature of the fluctuations,  $\mathbf{b}$ , and mean parts of the field, and their comparative strengths.

Balsara et al. (2004) and Balsara and Kim (2005) investigate the fluctuation dynamo, introducing a seed field of order  $10^{-3} \mu\text{G}$  and increasing it to  $10^{-1} \mu\text{G}$  over 40 Myr. This is insufficiently long to saturate and there is no mean field, but they do examine the turbulent structure of  $\mathbf{b}$  and the dynamo process.

However galactic differential rotation is a defining feature of the global characteristics of disc galaxies and is felt locally by the Coriolis effect and shearing in the azimuthal direction. There is observational evidence that the magnetic field in disc galaxies, which is heavily randomised by turbulence, is also strongly organized along the direction of the spiral arms (e.g. Patrikeev et al., 2006; Tabatabaei et al., 2008; Fletcher et al., 2011). Differential rotation is responsible for the spiral structure, so must be included to understand the source of the mean field in the galaxy.

There is also considerable controversy over the nature and even the existence of the the galactic dynamo. A fluctuation dynamo can be generated by turbulence alone, but it is not clear that it can be sustained indefinitely. The mean field dynamo cannot be generated without anisotropic turbulence and large scale systematic flows.

Gressel et al. (2008a); Gressel et al. (2008b) include differential rotation and by introducing a small seed field, are able to derive a mean field dynamo for a stratified ISM. The dynamo is only sustained in their model for rotation  $4\Omega_0$ , where  $\Omega_0 \approx 230 \text{ km s}^{-1}$  is the angular velocity of the Galaxy in the solar vicinity. Otherwise they apply parameters the same as or similar to the local Galaxy. Gressel (2008) also considered solid body rotation and found no dynamo, but concluded that shear, without rotation, cannot support the galactic dynamo. Without rotation diamagnetic pumping is too weak to balance the galactic wind. The resolution of the model at  $(8 \text{ pc})^3$  limits the magnetic Reynolds numbers available, which may explain the failure to find a dynamo with rotation of  $\Omega_0$ . For a comprehensive understanding of the galactic magnetic field differential rotation should not be neglected.

#### 2.4.5 Radiative cooling and diffuse heating

The multi-phase structure of the ISM would appear to be the result of a combination of the complex effects of supersonic turbulent compression, randomized heating by SNe and the differential cooling rates of the ISM in its various states. Although excluding SNe, and having a low resolution, Rosen, Bregman and Norman (1993) generated a multi-phase ISM with just diffuse stellar heating from the mid-plane and non-uniform radiative cooling.

Radiative cooling depends on the density and temperature of the gas and different absorption properties of various chemicals within the gas on the molecular level. For models such as the ones discussed here detailed analysis of these effects and estimates of the relative abundances of these elements in different regions of the ISM (see e.g. Wolfire et al., 1995) need to be adapted to fit a monatomic gas approximation. Stellar heating varies locally, on scales far below the resolution of these models, due to variations in interstellar cloud density and composition as well ambient ISM temperature sensitivities.

Subtle variations in the application of these cooling and heating approximations may have very unpredictable effects, due to the complex interactions of the density and temperature perturbations and shock waves. In particular thermal instability is understood to be significant in accelerating the gravitational collapse of dense clouds, by cooling the cold dense gas more quickly than the ambient diffuse warm gas.

Different models have used radiative cooling functions which are qualitatively as well as quantitatively distinct, making direct comparison uncertain. Vázquez-Semadeni, Gazol and Scalo (2000) compared their thermally unstable model to a different model by Scalo et al. (1998) who used a thermally stable cooling function. They concluded that thermal instability on  $1 \text{ pc}$  scales is insufficient to account for the phase separation of the ISM,

but in the presence of other instabilities increases the tendency towards thermally stable temperatures. Similarly, de Avillez and Breitschwerdt (2004) and Joungh and Mac Low (2006) compared results obtained with different cooling functions, but comparing models with different algorithms for the SN distribution and control of the explosions. In the absence of SNe driven turbulence the ISM does separate into two phases with reasonable pressure parity and in the presence of background turbulence this separation persists (Sánchez-Salcedo, Vázquez-Semadeni and Gazol, 2002; Brandenburg, Korpi and Mee, 2007). Although the pressure distribution broadens, the bulk of both warm and cold gases broadly retain pressure parity.

An additional complexity is advocated by de Avillez and Breitschwerdt (2010). Generally it is assumed that ionization through heating and recombination of atoms by cooling are in equilibrium. However recombination time scales lag considerably, so that cooling is not just dependent on temperature and density. Cooler gas which had been previously heated to  $T > 10^6$  K will remain more ionized than gas of equivalent density and temperature which has not been previously heated. de Avillez and Breitschwerdt (2010) show that this significantly affects the radiation spectra of the gas, therefore they use a cooling function which varies locally, depending on the thermal history of the gas.

The choice of cooling and heating functions has a quantitative effect on the results of ISM models and there is evidence that the inclusion or exclusion of thermal instability in various temperature ranges has a qualitative impact on the structure of the ISM. However uncertainty remains over whether the adopted cooling functions are indeed faithfully reproducing the physical effects. There is also uncertainty over how critical the differences between various parameterizations are to the results, once SNe, magnetic fields and other processes are considered. It is certain, however, that differential radiative cooling is an essential feature of the ISM.

## 2.4.6 Magnetism

Estimates of the strength of magnetic fields indicate that the magnetic energy density has the same order of magnitude as the kinetic and thermal energy densities of the ISM. Including magnetic pressure substantially increases the thickness of the galactic disc compared to the purely hydrodynamic regime. Magnetic tension and the Lorentz force will affect the velocities and density perturbations in the ISM. Ohmic heating and electrical conductivity will affect the thermal composition of the ISM. Hydrodynamical models provide an excellent benchmark, but to accurately model the ISM and be able to make direct comparisons with observations the magnetic field should be included.

Comparisons between MHD and HD models have been made (Korpi, Brandenburg, Shukurov and Tuominen, 1999; Balsara et al., 2004; Balsara and Kim, 2005; Mac Low et al., 2005; de Avillez and Breitschwerdt, 2005a). These either impose a relatively strong initial mean field or contain only a random field, and are evolved over a comparatively short time frame. So the composition of the field cannot reliably be considered authentic.

Ideally it would be useful to understand the dynamo mechanism; are there minimum and maximum rates of rotation conducive to magnetic fields? How does the SNe rate or distribution affect the magnetic field? What is the structure of the mean field, how do the mean and fluctuating parts of the field compare and how is the magnetic field related to the multi-phase composition of the ISM? To ensure the field is the product of the ISM dynamics the mean field needs to be generated consistently with the key ingredients of differential rotation and turbulence, from a very small seed field. The time over which the model evolves must be sufficiently long that no trace of the seed field properties persist.

### 2.4.7 Cosmic Rays

Cosmic rays are high energy charged particles, travelling at relativistic speeds. Their trajectories are strongly aligned to the magnetic field lines (Kulsrud, 1978). It is speculated that, amongst other potential sources, they are generated and accelerated in shock fronts around supernovae. They also occur in solar mass ejections, some of which are caught in the Earth's magnetosphere. The polar aurora result from these travelling along the field lines and heating the upper atmosphere as they collide.

Cosmic rays are of interest in themselves, but also are estimated to make a similar contribution to the energy density and pressures in the ISM as each of the magnetic field, the kinetic and the thermal energies (Parker, 1969). As such their inclusion can be expected to significantly affect the global properties of the ISM.

Although a substantial component of the ISM is not charged the highly energized cosmic rays strongly affect the bulk motion of the gas. The interaction between cosmic rays and the ISM is highly non-linear, but can be considered in simplified form by a diffusion-advection equation,

$$\frac{\partial e_{\text{cr}}}{\partial t} + \nabla(e_{\text{cr}}\mathbf{u}) = -p_{\text{cr}}\nabla\mathbf{u} + \nabla(\hat{K}\nabla e_{\text{cr}}) + Q_{\text{cr}}, \quad (2.1)$$

$$p_{\text{cr}} = (\gamma_{\text{cr}} - 1)e_{\text{cr}}, \quad (2.2)$$

where  $e_{\text{cr}}$  and  $p_{\text{cr}}$  are the cosmic ray energy and pressure respectively, and  $\hat{K}$  the cosmic ray diffusion tensor,  $\gamma_{\text{cr}}$  the cosmic ray ratio of specific heats, and  $Q_{\text{cr}}$  a cosmic ray source term such as SNe.  $\mathbf{u}$  is the ISM gas velocity.

Hanasz et al. (2004, 2005, 2006, 2011) use cosmic rays in a magnetized isothermal simulation to perturb the magnetic field and drive the dynamo in their global disc galaxy simulations. None of the thermodynamic, stratified models of the ISM have yet included cosmic rays.

### 2.4.8 Diffusivities

The dimensionless parameters characteristic of the ISM, such as the kinetic and magnetic Reynolds numbers (reflecting the relative importance of gas viscosity and electrical

resistivity) and the Prandtl number (quantifying thermal conductivity) are too large to be obtainable with current computers. Lequeux (2005) estimates the Reynolds number  $Re \simeq 10^7$  for the cold neutral medium, with viscosity  $\nu \simeq 3 \times 10^{17} \text{ cm}^2 \text{ s}^{-1}$ . Uncertainty applies to these estimates in the various phases and also to thermal and magnetic diffusivities, but physical  $Re$  and  $Rm$  (magnetic Reynolds number) are far larger and diffusivities far smaller than can be resolved numerically. Given the very low physical diffusive co-efficients in the ISM some models approximate them as zero. Applying ideal MHD where electrical resistivity is ignored (e.g. de Avezil, 2000; Mac Low et al., 2005; Joungh and Mac Low, 2006; Li, Mac Low and Klessen, 2005, and their subsequent models) the magnetic field is modelled as frozen in to the fluid. Although magnetic diffusion is not explicitly included in their equations, it exists through numerical diffusion which is determined by the grid scale. In models with adaptive mesh refinement, the diffusion varies locally with the variations in resolution.

In fact, within the turbulent environment of the ISM, although the diffusivity is very low, shocks and compressions can create conditions, in which the time scales of the diffusion are comparable with other time scales such as the diffusion of heat, charge and momentum. Korpi, Brandenburg, Shukurov, Tuominen and Nordlund (1999) and Gressel et al. (2008a) include bulk diffusivity in their equations, which are some orders of magnitude larger than those typical of the ISM. These are constrained by the minimum that can be resolved with the numerical resolution available, but ensure the level of diffusion is consistent throughout.

Although, the maximum effective Reynolds numbers are much lower than estimates for the real ISM, there is considerable consistency in structures derived by models on the meso-scales, e.g., thickness of the disc, size of remnant structures and super bubbles, typical velocities, densities and temperatures. Uncertainties are greater in describing the fine structures; remnant shells, condensing clouds, and dispersions of velocity, density and temperature.

## 2.4.9 The galactic fountain

It is reasonable to conclude from what we understand from observations and the work of de Avezil and Mac Low (2002) and their subsequent models, that the modelling of the galactic fountain requires a scale height of order  $\pm 10$  kpc. They found  $z = \pm 5$  kpc was insufficient to establish a duty cycle with hot gas condensing and recycling back to the disc. Gressel et al. (2008a) model the ISM to  $z = \pm 2$  kpc and throughout their model there is a net outflow across the outer horizontal surfaces.

Less clear is how large a horizontal span is required. Korpi, Brandenburg, Shukurov, Tuominen and Nordlund (1999) found the correlation length of the velocity of the hot gas increased from about 20 pc at  $z = 0$  to about 150 pc at  $|z| = 300$  pc and the scale of the box at  $|z| = 850$  pc. This indicates that as height increases above 1 kpc the size of the physical structures of the hot gas may well exceed the model. As such reliable modelling

of the galactic fountain may well require a substantially larger computational domain in all directions. de Avillez and Mac Low (2002) model large  $|z|$  with much lower resolution than the mid-plane, to manage the computational demands. It may be that the scale of the task may necessitate sacrificing resolution throughout to expand the range of the models to investigate the galactic fountain.

#### **2.4.10 Spiral arms**

Only models on the larger scales previously described (Slyz, Kranz and Rix, 2003; Dobbs and Price, 2008; Hanasz et al., 2004, and subsequent models) have reproduced features similar to the spiral arms in rotating galaxies. It is unlikely that the dynamics of the spiral arms can be understood from models in the scale of 1–2 kpc in the horizontal, because they are structures typical of the full size of the galaxy. Rather than an outcome of such models, they could perhaps be included as an input in the form of a density wave through the box at appropriate intervals, with other associated effects, such as fluctuations in SNe rates.

### **2.5 Summary**

Many models have been used, some to describe different astrophysical features or alternative approaches to the same environment. Direct comparison of results is consequently difficult. All models must omit ingredients and approximate or parameterize some of the challenging dynamics. Computational power restricts resolution, domain size and physical components, so each model must be adapted to match the requirements of the particular astrophysics under investigation; e.g. star formation permits only a small domain, enables high resolution, requires thermal instability; spiral arms impose the requirement of a global domain, restrict resolution or turbulence. A comprehensive understanding requires a hierarchy of models, spanning an overlapping range of scales, encompassing the all the critical physical features.

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