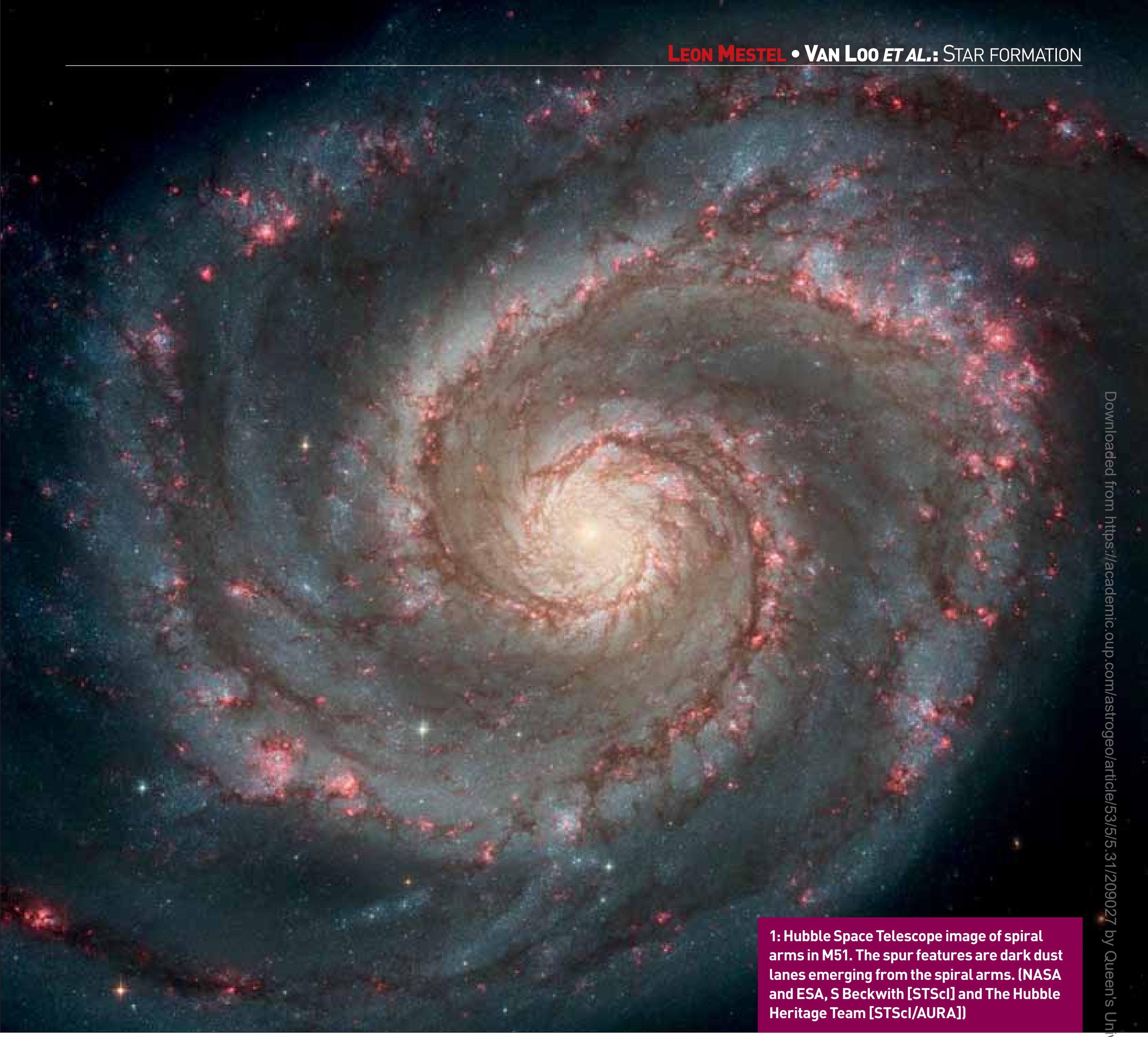


1: Hubble Space Telescope image of spiral arms in M51. The spur features are dark dust lanes emerging from the spiral arms. (NASA and ESA, S Beckwith [STScI] and The Hubble Heritage Team [STScI/AURA])

Magnetic fields and star formation

LEON MESTEL: Building on ideas first explored by Leon Mestel, Sven Van Loo, Tom Hartquist and Sam Falle examine the role of magnetic fields on the formation of clumps, discs and stars.

The role of magnetic fields in star formation was addressed by Mestel and Spitzer (1956), who were aware that the results of polarization studies of the radiation from stars obscured by interstellar dust imply the presence of an interstellar magnetic field. They also cited Fermi (1949) on cosmic-ray acceleration in magnetized media and Chandrasekhar and Fermi (1953) on the equilibrium of spiral arms due to a balance of gravity by thermal, magnetic and turbulent pressures. Mestel and Spitzer (1956) estimated the minimum mass of a cold, perfectly conducting, magnetized interstellar cloud with sufficient self-gravity to drive collapse.

Furthermore, Mestel and Spitzer addressed a possibly important role, in star formation, of a non-ideal magnetohydrodynamic (MHD) mechanism called ambipolar diffusion. It is the motion, driven by electromagnetic forces, of charged particles relative to neutrals. In a weakly ionized medium the rate per unit volume at which collisions transfer momentum between neutrals and a species of charged particles is proportional to the product of the neutral number density and the number density of charged particles of that species. For a given electromagnetic force per unit volume, the charged particle drift speed relative to the neutrals increases as the inverse of the charged particle number density. This relative motion reduces the magnetic flux in the region and can result in the collapse of an object that initially had too strong a magnetic field to collapse otherwise.

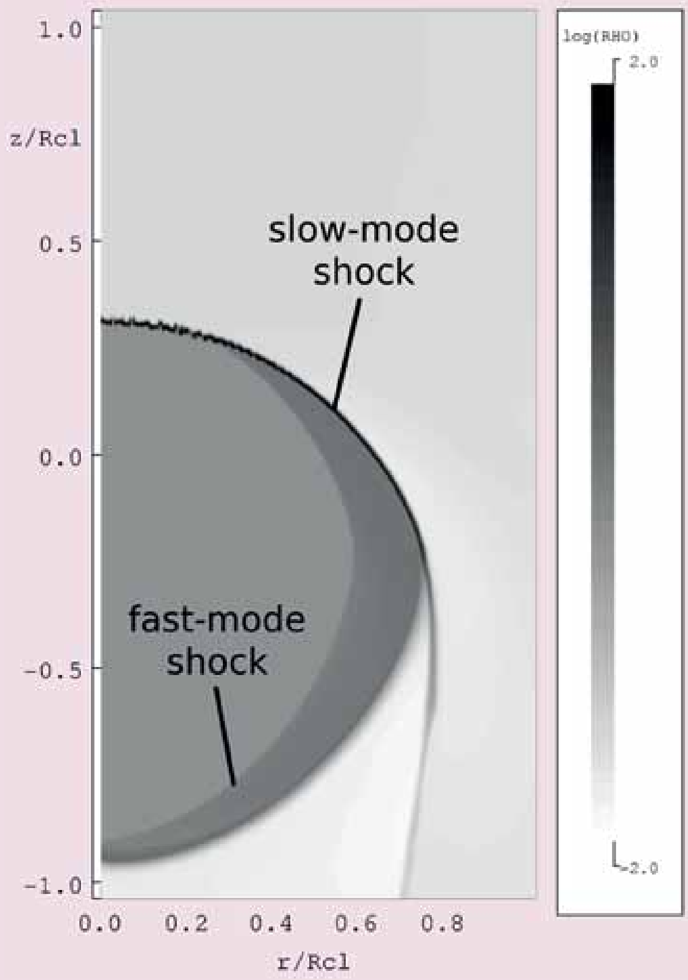
In the mid-1960s, Leon wrote twin papers summarizing the state of the theory of star formation (Mestel 1965a, b). In the second of these, he identified a comprehensive programme of work on the theory of star formation in a magnetized interstellar medium. One mechanism that he highlighted is the transport of angular momentum by the magnetic field, a topic that he explored further in a series of papers concluding with Mestel and Paris (1979, 1984).

Much of Leon's work on star formation concerns the evolution of a pre-formed clump that might be the immediate progenitor of a protostar. Objects called dense cores are such progenitors, and they and their evolution are addressed below. However, magnetic fields play roles in the formation of the giant molecular clouds (GMCs), in which dense cores exist, and in the emergence of the dense cores themselves. Consequently, the generation of GMCs and dense cores receives attention before the magnetic processes in dense core collapse are addressed. As a star is born and undergoes its early development, it loses mass in an outflow. The outflow from a young star drives a shock into dusty molecular material surrounding it. The theoretical and computational treatment of the shock requires the adoption of a multi-component model in which the ambipolar diffusion of the charged dust must be included.

Formation of giant molecular clouds

Simulations of galactic formation including feedback from star formation indicate that spiral arms can appear in the absence of magnetic fields (e.g. Agertz *et al.* 2011). However, the inclusion of a seed magnetic field in such a simulation leads to similar structure while amplification of the field occurs until its strength is comparable to that of the magnetic field in the diffuse phases of the interstellar medium (e.g. Wang and Abel 2009).

Our galaxy contains more than a thousand giant molecular clouds, which are concentrated in the spiral arms. The large-scale molecular distribution in the Rosette Molecular Cloud, a relatively nearby GMC, has been thoroughly studied (Williams *et al.* 1995). Its full extent is somewhat under 100 pc and it contains of the order of 10^5 solar masses. The mean molecular hydrogen number density, n(H_2), is roughly 25 cm^{-3} and most of the mass is concentrated in about 70 translucent clumps with masses ranging from a few tens to a few thousands of solar masses and n(H_2) typically about 220 cm^{-3} and *T*, the temperature, around 10 K. Heyer and Brunt (2012) found evidence for magnetically aligned velocity anisotropy in ^{12}CO emission features formed in low surface brightness regions of another GMC, the Taurus Molecular Cloud (TMC), and concluded that β, the ratio of the thermal pressure to the magnetic pressure, in such regions is very small compared to unity. They did not find evidence of substantial anisotropy in ^{13}CO emission features, which they noted probably trace regions with visual extinctions between 4 and 10 magnitudes.



2: Fast and slow-mode shocks propagating through an axisymmetric cloud. (Van Loo *et al.* 2007 *A&A* 471 213; reproduced with permission ESO)

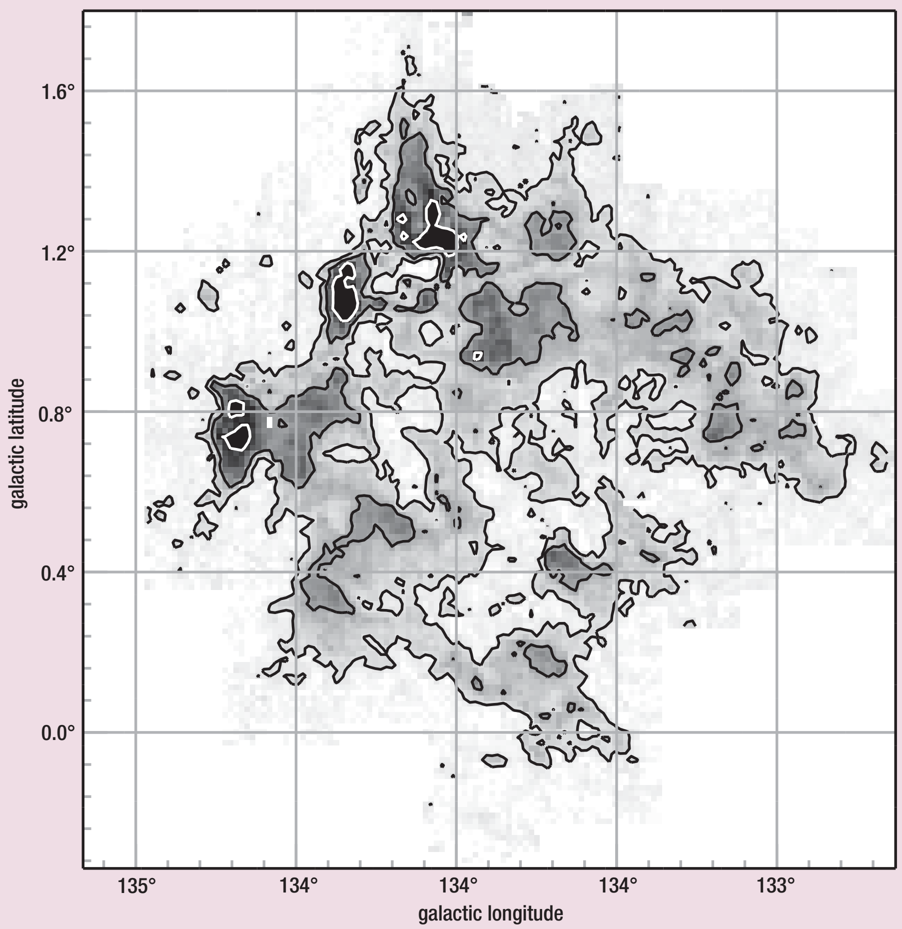
Two classes of models for GMC formation exist. In the top-down models, large-scale gravitational, thermal and magnetic instabilities in the differentially rotating disc of a galaxy trigger the initiation of GMCs. The Parker instability, which leads to undulations in the magnetic field lines supporting material in a constant gravitational field perpendicular to them, is one of the instabilities that may play a key part (e.g. Mouschovias *et al.* 2009). In bottom-up models, compression in converging flows or compression of finite structures by supernova remnant or superbubble-driven shocks trigger GMC formation. Observations of CO in the grand design spiral M51 favour a top-down formation mechanism (Koda *et al.* 2009). However, the relative importance of top-down and bottom-up mechanisms may depend on the galactic environment (e.g. Dobbs 2008).

Adopting a top-down approach, Kim and Ostriker (2002) performed MHD simulations of a self-gravitating, magnetized, differentially rotating, thin, isothermal, gaseous disc passing through a rigidly rotating gravitational potential like that of a local segment of a tightly wound trailing spiral arm. Sufficiently deep rigidly rotating potentials lead to shock formation. They examined the gravitational instability occurring under certain conditions in the postshock gas.

The Toomre *Q* parameter is a measure of the axisymmetric stability of a rotating unmagnetized disc of uniform density. It is given by $Q=\kappa c_s/\pi G\Sigma$ where κ, c_s, *G* and Σ are respectively the epicyclic frequency, the sound speed, the gravitational constant and the mass surface density. For a Keplerian disc, the epicyclic frequency and the orbital angular frequency, Ω, are equal.

For each of several sets of parameters, e.g. spiral potential strength and preshock β, Kim and Ostriker (2002) determined the critical value of *Q* in the postshock region below which gravitational instability occurs. The strength of the spiral potential is parameterized by $F=2F_1/\sin(i)$, where $F_1=\Phi_0/(\Omega R_0)^2$, *i* is the pitch angle of the spiral, Φ_0 is the magnitude of the depth of spiral potential and R_0 is the radius of the orbit. The inclusion of the magnetic field lowers the critical value of *Q*. For an unmagnetized medium and $F_1=0$, the critical value of *Q* is 1, and for $\beta=1$ and $F_1=0$, the critical value of *Q* is 0.7. For an unmagnetized medium and $F_1=0.06$, the critical value of *Q* is 2.8, and for $\beta=1$ and $F_1=0.06$, the critical value of *Q* is 0.4. All quantities mentioned in the preceding few sentences refer to upstream, unperturbed quantities.

In addition, Kim and Ostriker (2002) showed that the nonlinear growth of self-gravitating perturbations results in the emergence of spur-like structures in the magnetized models. Such



3: ^{12}CO map of W3 GMC. (Van Loo *et al.* 2007 *A&A* 471 213; reproduced with permission ESO)

structures are commonly observed in spiral galaxies. An example of a spiral galaxy in which such spurs occur is shown in figure 1. Kim and Ostriker (2002) attributed the growth of the spurs to the magneto-Jeans mechanism, which leads to the magnetic tension force opposing the Coriolis force. In the absence of a magnetic field, the Coriolis force would prevent the coalescence of matter along a spiral arm. Consequently, magnetic effects seem essential for spur formation. The spurs in the magnetized models undergo fragmentation to form 4×10^6 solar mass clumps, which may fragment further into GMCs.

In attempts to understand how GMCs might form in bottom-up scenarios, several groups have simulated the production of GMC-like cloud material in supersonic collisions of streams of magnetized gas that is initially in the warm phase with temperatures of several thousand degrees. Heitsch *et al.* (2009) conducted one of the more recent studies of this type. Vázquez-Semadeni *et al.* (2011) have included ambipolar diffusion in such simulations. For a given heating rate per particle, the warm phase exists only at pressures below a specific maximum pressure determined by that heating rate, and at pressures above that specific maximum pressure the cloud phase is the only stable phase. In the local interstellar medium the thermal pressure of the warm gas and the atomic clouds is only a factor of a few or less below the relevant maximum pressure, which is about a few eV cm^{-3}. A moderately supersonic collision of two streams of the warm gas would lead to most of it undergoing a phase transition and becoming cold. Shocks exist on either side of the contact discontinuity separating the material in the two streams. In a non-magnetic simulation, the material in one stream passes through one of these shocks, while the material in the other stream passes through the other. The shocked gas is at a higher pressure than the unshocked gas in the streams. It becomes thermally unstable and cools. If the relative velocity of the unshocked material in the two streams is along a large-scale uniform magnetic field, the cooling leads to a compression of about a hundred or more. If the preshock β has a value of unity and the relative velocity of the unshocked material in the streams is perpendicular to a large-scale magnetic field, the compression is more modest and the postshock regions have low values of β, which depend on the Mach number of the relative velocity.

The roles of slow-mode shocks and fast-mode shocks in bottom-up models of GMC formation were revealed in axisymmetric simulations, performed by Van Loo *et al.* (2007), of shocks interacting with individual initially spherical uniform clouds. Three wave modes exist in ideal MHD: fast, slow and intermediate. Unsurprising, the fast-mode waves are the fastest. A different type of shock is associated with each of the wave-modes, and the minimum speed differs for each wave-mode and depends on the angle between the wavevector and the upstream magnetic field. Note that intermediate-mode shocks are not evolutionary (e. g. Falle and Komissarov 2001) and should be ignored.

In each of the Van Loo *et al.* (2007) simulations, a shock initially propagates into a tenuous upstream medium in pressure equilibrium with a spherical cloud of warm phase gas. The upstream magnetic field is parallel to the shock velocity and is uniform in the upstream tenuous medium and the spherical cloud. Figure 2 shows the positions of the fast-mode shock and slow-mode shock surfaces after both shocks have started to propagate into the cloud. Compression during cooling behind the fast-mode shock is moderate, and the cooled postshock material is at low β, as is consistent with the results of the observational study of the Taurus Molecular Cloud mentioned above. The compression behind the slow-mode shock is substantial, and behind it β approaches unity. The general morphology of the simulated shocked cloud is similar to that shown in figure 3, which displays a CO map of the W3 molecular cloud.

Van Loo *et al.* (2010) have produced 3D simulations that are analogous to those of Van Loo *et al.* (2007). One conclusion drawn by Van Loo *et al.* (2010) is that a shock propagating moderately obliquely to the magnetic field produces a cooled cloud similar to a cloud formed behind a shock that propagates perpendicular to the magnetic field. Another significant conclusion is that the fast-mode Mach number must be between roughly two and three, if the cold cloud is to be reasonably long-lived and have a substantial fraction of its volume contained in regions of low β. Shocks with higher Mach numbers would lead to cold cloud lifetimes that are too short. Weaker shocks do not result in much of the cloud material having a particularly small β.

Formation of dense cores

Dense cores, having temperatures of about 10 K and masses of roughly 1 to 10 solar masses each and in which $n(H_2)$ is roughly 10^4–10^5 cm^{-3} (e.g. Benson and Myers 1989), are considered to be the progenitors of low-mass stars: those stars with less than four solar masses. More massive cores in which clusters of stars are born also exist. Of course, self-gravity is important in the formation of clusters. Fiedler and Mouschovias (1993) included ambipolar diffusion in an axisymmetric model of the formation of a flattened, magnetized dense core due to the gravitational collapse of a more diffuse distribution of gas. They also followed the evolution until the central number density was several orders of magnitude higher than those mentioned above.

There exists a vast literature on the formation, due to the evolution of nonlinear MHD perturbations, of structures within clumps having properties similar to the translucent clumps in GMCs (e.g. Ballesteros-Paredes *et al.* 2007). To understand what processes occur in such simulations, it is normally useful to perform a linear analysis, similar to that conducted by Mouschovias *et al.* (2011) to gain insight into waves in weakly ionized media. Many of the ideal MHD simulations of the formation of core-like structures have been based on the assumption that the perturbations are on background media in which β is small. Thus, Falle and Hartquist (2002) performed a linear analysis of ideal MHD perturbations in a medium with a small β. If β is small, in a fast-mode, linear perturbation, the ratio of the magnitude of the density perturbation to the density is of the same order as the ratio of the magnitude of the velocity perturbation to the Alfvén speed. In a slow-mode, linear perturbation in a low β region, the ratio of the magnitude of the density perturbation to the density is of the same order of $\beta^{-1/2}$ times the ratio of the magnitude of the velocity perturbation to the Alfvén speed. Falle and Hartquist (2002) reported the results of plane-parallel, time-dependent simulations showing that the nonlinear steepening of a fast-mode wave with a finite but modest amplitude can readily excite slow-mode waves as long as the angle between the fast-mode wavevector and the magnetic field is neither too large nor too small. The slow-mode excitation produces persistent inhomogeneities with large density contrasts.

In an extension of the work of Falle and Hartquist (2002), Lim *et al.* (2005) included ambipolar diffusion and took each initial perturbation to be a nonlinear fast-mode wave. The neutral-ion momentum transfer timescale is the timescale over which a neutral particle, subjected to no forces other than friction due to collisions with ions, decelerates. It is inversely proportional to the ion number density. Lim *et al.* (2005) defined a lengthscale, l_d, given by that timescale times the speed of Alfvén waves having frequencies that are much lower than the inverse of that timescale. In a translucent clump or dense core the value of l_d would typically be of order 0.01 pc. Lim *et al.* (2005) found that in a medium with β of about 0.01, ambipolar diffusion substantially reduces the maximum density arising from the evolution of any fast-mode wave with an initial wavelength of less than several hundred times l_d and an initial velocity amplitude having a magnitude less than the Alfvén speed.

Van Loo *et al.* (2008) carried out 2D simulations to examine the effect of ambipolar diffusion on the formation of structure through the generation of slow-mode disturbances by the nonlinear steepening of initial fast-mode perturbations. A number of their results are in harmony with those of Lim *et al.* (2005). In addition, they argued that substructure within cores, like that seen in core D of TMC-1 (Peng *et al.* 1998), can be generated by slow-mode excitation due to the nonlinear steepening of fast-mode waves only in cores with unusually high fractional ionizations. They also noted that the presence of fast-mode perturbations in the intercore gas and the association of dense cores with slow-mode structures account for the transition from superthermal linewidths in the intercore medium to thermal linewidths in the cores (Myers 1983).

Li *et al.* (2012) have incorporated ambipolar diffusion in 3D simulations of the power spectrum of MHD waves in a background medium with $\beta = 0.1$. The maximum amplitudes are sub-Alfvénic but superthermal. Using ideal MHD results and non-ideal MHD results as input, Li *et al.* (2012) have performed radiative transfer calculations to produce synthetic CS $J = 2\text{-}1$ and $H^{13}CO^+$ $J = 1\text{-}0$ line profiles. They have concluded that an observable narrowness of ion line profiles relative to neutral line profiles can arise due to ambipolar diffusion. Downes (2012) has also addressed the effects of ambipolar diffusion on the wave spectrum in a star-forming region and has included dust grains as a separate fluid.

Magnetic reconnection in a medium with a spectrum of nonlinear waves, like that studied by Li *et al.* (2012), has received attention recently (e.g. Santos-Lima *et al.* 2010). However, Santos-Lima *et al.* (2010) have considered Ohmic dissipation only and have neglected ambipolar diffusion. This is an important distinction because Ohmic diffusion can lead to reconnection, whereas ambipolar diffusion cannot.

Dense core collapse

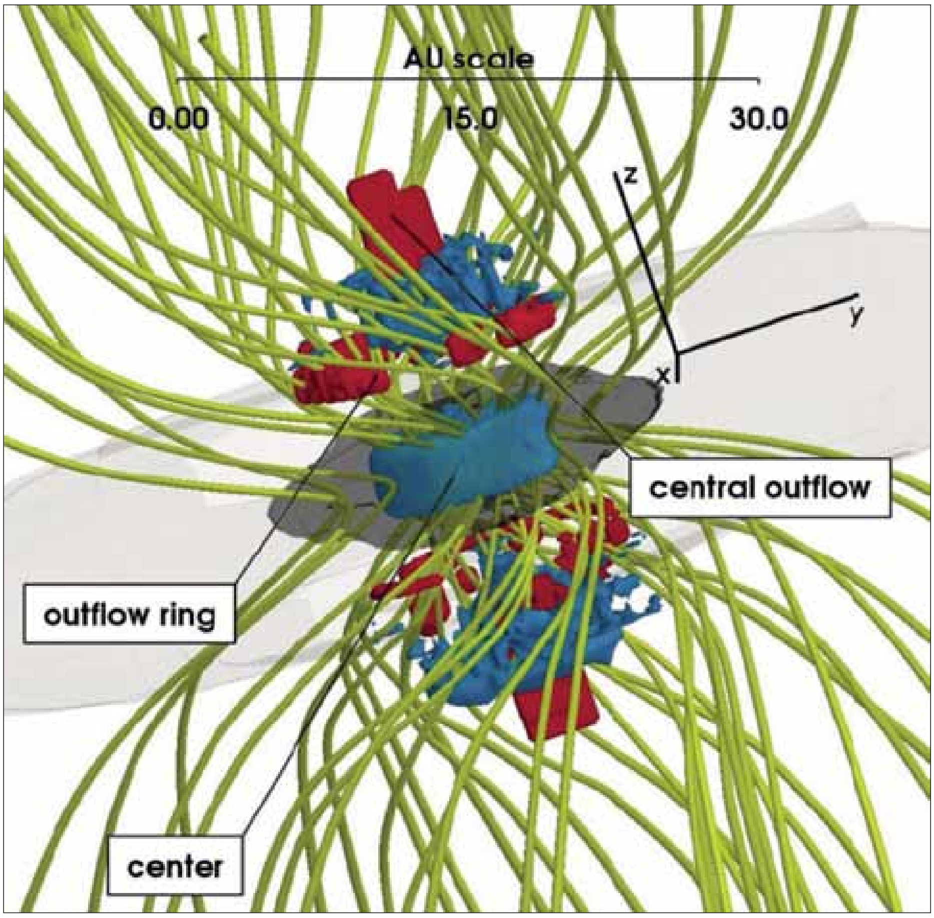
The self-gravity of a dense core plays a central part in star formation. An isothermal, spherical, uniform density, perfectly conducting core threaded by a uniform magnetic field and surrounded by a very tenuous medium having a constant pressure is not in equilibrium. Mouschovias (1976) found isothermal, perfectly conducting, axisymmetric equilibrium states with the same distributions of mass on the magnetic field lines as the corresponding uniformly magnetized spheres. Mouschovias and Spitzer (1976) showed that such an axisymmetric core with a mass-to-magnetic flux ratio below a critical value does not collapse because of self-gravity, even if it is cooled to absolute zero and the surrounding tenuous medium has an indefinitely high uniform pressure. That critical value is $0.53(5/G)^{1/2}/3\pi$. Structures with a mass-to-flux ratio above (below) that are said to be magnetically supercritical (subcritical). Mouschovias and Tassis (2010) have addressed the difficulty in inferring from observational data whether a core is magnetically supercritical or subcritical.

If embedded in surroundings with sufficiently high pressures, a supercritical core will collapse on roughly a gravitational free-fall time. In such a case, the main role of the magnetic field will be in angular momentum transport. Differential rotation will drive MHD waves that carry away angular moment (Mestel 1965b, Mestel and Paris 1979, 1984).

The collapse of a magnetically subcritical core, as ambipolar diffusion leads to an increase in the mass-to-flux ratio, has received considerable theoretical attention. Basu and Mouschovias (1995a, b) presented results of axisymmetric thin disc simulations of ambipolar-diffusion regulated collapse including angular momentum transport for a wide range of parameters. The vertical structure of a disc was assumed to be in static equilibrium. They adopted a two-fluid description. At the same time Ciolek and Mouschovias (1995) published results of multi-fluid, axisymmetric simulations of the ambipolar-diffusion regulated collapse of non-rotating thin discs. They included neutral-gas, ion, electron, charged-grain and neutral-grain fluids and adopted a chemical network in order to calculate the ion and electron abundances and the charge distributions on grains. At fractional ionizations of about 10^{-8} and below, the frequency at which a neutral particle collides with grains is greater than that at which it collides with ions; then grain-neutral drag dominates over ion-neutral drag and controls the ambipolar diffusion. An additional complication arises because the timescale in a dense core for a 100 nm grain to encounter a mass of neutral particles comparable to its own is about the same as its gyroperiod. The inverse of the ratio of those two timescales is called the Hall parameter.

In the general picture that has emerged, ambipolar-diffusion induced dynamics results in an outwardly propagating C-type MHD shock (Li and McKee 1996), which is sometimes referred to as the “magnetic diffusion shock”. In axisymmetric models neutral material, closer to the symmetry axis than this shock, falls inwardly at nearly the free-fall speed until the centrifugal force becomes important and triggers the formation of a hydrodynamic shock that decelerates the infalling matter and potentially allows a Keplerian disc to form (Shu *et al.* 1987).

To show that the angular momentum transport during the formation of a low-mass star is neither too efficient nor too inefficient for a protoplanetary disc to develop, Dapp *et al.* (2012) have recently extended the work of Basu and Mouschovias (1995a, b) by including the effects of neutral and positively and negatively charged grains on ambipolar diffusion. Rather than computationally solve fluid equations for the ions, electrons and grains, they derived appropriate diffusion terms to incorporate in the magnetic induction equation. Such terms moderate the effectiveness of the angular momentum transfer. The calculation of those terms required that the inclusion of a network



4: Jet and protostellar disc formation simulation including ambipolar diffusion. The grey surfaces show the disc with outflow velocity contours between 0.01 and 0.4 km s^{-1} in red. The magnetic field is represented by green tubes. (From Duffin and Pudritz 2009; reproduced by permission of the AAS)

for the chemistry involving charged species. This approach allowed them to study a problem in which the highest density is 16 orders of magnitude higher than the lowest density. They found that ambipolar diffusion dominates diffusion up to a number density of about $5\times10^{12}\,\mathrm{cm}^{-3}$, but at higher densities Ohmic dissipation is more important. Their primary result is the demonstration that protoplanetary discs can form in a model incorporating ambipolar diffusion and Ohmic dissipation.

Dapp *et al.* (2012) did not include the Hall diffusion term in their magnetic induction equation. The Hall term is associated with a current component that, in the neutral frame, is perpendicular to the magnetic field and the electric field. It is important when the Hall parameter is of order unity or smaller. Braiding and Wardle (2012) have found similarity solutions describing the evolution of a magnetized, rotating, thin, isothermal disc in an analysis including Hall diffusion and diffusion driven by a combination of ambipolar diffusion and Ohmic dissipation. Braiding and Wardle (2012) have concluded that reasonable assumptions about the Hall diffusion can lead to a change of the size of the protoplanetary disc that appears by up to an order of magnitude relative to what it would be if Hall diffusion were not included.

Another source of diffusivity that might affect angular momentum transport has been considered by Santos-Lima *et al.* (2012). They have suggested that magnetic reconnection, occurring due to the presence of a spectrum of nonlinear waves, can result in an effective diffusivity that would reduce the efficiency of the angular momentum transport by MHD waves arising due to differential rotation. Seifried *et al.* (2012b) have argued that reconnection is unimportant but that the presence of a background spectrum of nonlinear waves affects the efficiency of angular momentum transportation by MHD waves in any case.

While Dapp *et al.* (2012) and Braiding and Wardle (2012) adopted a thin disc approximation, Duffin and Pudritz (2009) studied protoplanetary disc formation by performing a 3D, adaptive mesh refinement, MHD simulation including ambipolar diffusion. The initial state was magnetically supercritical and similar to a rotating Bonner–Ebert sphere, and Duffin and Pudritz (2009) did not take grains into account when calculating the ambipolar diffusivity. They appear to have neglected the Ohmic and Hall diffusivities. They found that a disc formed and that a two-sided jet also developed. They also considered the formation of binaries and drew conclusions similar to those of Hosking and Whitworth (2004). Those authors' 3D MHD simulation, including ambipolar diffusion, of the collapse of an initially magnetically subcritical core had already indicated that the magnetic removal of angular momentum inhibits fragmentation. Ideal MHD simulations performed by Price and Bate (2007) also imply that the transport of angular momentum by magnetic fields suppresses fragmentation, but they concluded that fragments appear if sufficiently large initial perturbations are present.

Outflows, shocks, dust, ionization

As mentioned above, Duffin and Pudritz (2009) found that a jet developed in their simulations. Figure 4 shows a schematic representation of the general structure of the disc and outflow arising in their simulations. Seifried *et al.* (2012a) worked on the development of a general outflow criterion, bearing in mind particularly the application to the early phases of high-mass star formation. They performed simulations with different initial rotational and magnetic energies. Initially weak fields or high rotational energies lead to well-collimated, fast jets. In contrast, initially strong fields result in poorly collimated, low-velocity outflows. Fast jets are associated with Keplerian protostellar discs. All of the outflows are launched from the discs by centrifugal acceleration, and the toroidal magnetic field component contributes increasingly to the gas acceleration further away from the discs. The poor collimation of the outflows in runs with strong initial magnetic fields is due to the hoop stresses being weak as a consequence of the slow build-up of a toroidal magnetic field component when the disc rotation is markedly sub-Keplerian.

Outflows are ubiquitous in star-forming regions and drive shocks into the magnetized, weakly ionized media surrounding young stars. Mullan (1971) recognized the importance of ambipolar diffusion in shocks driven into weakly ionized astrophysical media. Draine (1980) and Chernoff *et al.* (1982) included a great deal of the relevant microphysics in shock models incorporating ambipolar diffusion. The compilation of equations and rates by Draine *et al.* (1983) enabled others to develop multifluid MHD models of shocks in star forming regions.

In a weakly ionized, magnetized star-forming region, a shock with a speed of less than about 40 km s^{-1} contains a smooth flow in which none of the ion, electron, neutral or grain components develop thin subshocks with thicknesses established by scattering mean free paths. Such shocks with continuous flow variables are called C-type shocks. They are important for feedback in star-forming regions, and sputtering and grain–grain collisions in them inject material contained in grain mantles and refractory cores into the gas phase (e.g. Schilke *et al.* 1997, Gusdorf *et al.* 2008).

The papers cited in the previous two paragraphs all concern models of perpendicular shocks, those that propagate perpendicular to the upstream magnetic field. Though the treatment of grain dynamics used by Draine *et al.* (1983) and authors who followed their approach is adequate for a wide range of interesting shock conditions, Pilipp *et al.* (1990) demonstrated the necessity of treating grain dynamics in perpendicular shock models more rigorously in many situations in which the Hall parameter of the grains is of order one or less. They treated each grain component as a fluid. The most sophisticated perpendicular shock models are those used by Guillet *et al.* (2011) to study grain destruction. They employed a Monte Carlo approach to follow the grain dynamics and charging, and included all components of the currents carried by the grains in the calculation of the magnetic field.

Pilipp and Hartquist (1994) recognized the necessity for the development of a treatment of oblique shocks comparable to that introduced by Pilipp *et al.* (1990) for perpendicular shocks. Wardle (1998) elucidated the grounds for difficulties encountered by Pilipp and Hartquist (1994) when trying to obtain solutions corresponding to fast-mode shocks. Those grounds presented challenges for the construction of fast-mode shock models in situations when local equilibrium does not obtain. Falle (2003) developed a technique, suitable for appropriate values of the grain Hall parameters, for dealing with the model equations governing the time-dependent evolution of a plane-parallel oblique MHD shock propagating into a weakly ionized dusty medium. Van Loo *et al.* (2009) took the first step to apply it with the inclusion of a treatment of the grain charging, ionization structure and cooling. Ashmore *et al.* (2010) and Van Loo *et al.* (2012) used the technique in the study of the interactions of oblique shocks with density variations and in the investigation of the dependence of grain destruction on the obliqueness of the shock, respectively.

Chen and Ostriker (2012) have argued that as a C-type shock forms, for example in a collision between two clumps or cores, the mass-to-flux ratio increases throughout some of the shock structure. The increase will persist for a time comparable to the final steady C-shock thickness divided by the drift speed, through the shock, of the ions with respect to the neutrals. They have suggested that under favourable conditions, the transient regions may be magnetically supercritical and collapse on timescales shorter than the relevant timescales for the shocks to evolve enough for the mass-to-flux ratios to decrease substantially. Thus, star formation would be triggered.

High-mass stars affect their environments with their radiation fields as well as their outflows. Williams and Dyson (2001) examined the internal structures of stationary ionization fronts with oblique upstream magnetic fields and found solutions only for upstream parameters in a range allowed by the evolutionary conditions that they identified. Overheating in some fronts can lead to some of the solutions not corresponding to resolved internal structures, even if those solutions are allowed by the evolutionary conditions. The inclusion of subshocks can lead to some, but not all, of these jumps being realized.

Several 3D simulations of magnetized ionization fronts have been reported. Krumholz *et al.* (2007) performed the first 3D, global simulation of an HII region expanding into a magnetized medium and found that magnetic fields suppress the sweeping up of gas perpendicular to magnetic field lines. This leads to small density contrasts and weak shocks at the leading edge of an HII region's expanding shell. Henney *et al.* (2009) reported the results of 3D MHD simulations of the photoionization of a molecular globule by an external ultraviolet source. They showed that, for a strong ionizing field, significant deviations from the non-magnetic evolution are seen if the pressure of the initial magnetic field threading the globule is greater than a hundred times the gas pressure. Mackey and Lim (2011) investigated the effects of initially uniform magnetic fields on the formation and evolution of dense pillars and cometary globules at the boundaries of HII regions. Like Henney *et al.* (2009), they found that only a strong initial magnetic field can significantly alter the dynamics. From simulations of a magnetized, collapsing region in which radiative feedback occurs, Price and Bate (2009) concluded that a strong magnetic field and radiative feedback leads to a star-formation rate of less than or about equal to 10% per free-fall time.

Conclusions

This brief review contains multiple references to work based on numerical computations that would have been unfeasible when Leon was doing his earliest seminal work on magnetic fields in star formation. That the purposes of many of the recent calculations have been the exploration of mechanisms considered by Leon is a testament to his physical insight. ●

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