



# Editorial: The Role of Magnetic Fields in the Formation of Stars

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## Editorial on the Research Topic

### The Role of Magnetic Fields in the Formation of Stars

The subject of how stars and planets form is one of the most fundamental outstanding questions in astronomy. Many theories have been proposed to explain the various processes involved. One of the key unanswered aspects of this whole question is exactly what role magnetic fields play in the overall process. It has been known for many years that magnetic fields exist in the interstellar medium, although their role is hotly debated.

Some theories have magnetic fields as the key agents of evolution, whilst other theories ignore magnetic fields altogether, as being only a minor perturbation on an otherwise turbulent picture. However, the recent advent of new telescopes capable of measuring inter-stellar magnetic fields, with previously unheard-of sensitivity and resolution, such as ALMA, NOEMA, CARMA, SMA, and new instruments on existing ground-based telescopes such as JCMT, Nobeyama and IRAM, and airborne/space-based telescopes such as SOFIA and Planck, has meant that it is now possible to revisit this question with fresh eyes, based on new data. In addition, the huge increase in the power of High-Performance Computers (HPCs) means that the current generation of simulations can include more details of more aspects of astrophysics than ever before.

In this Research Topic we revisit the question of the role of magnetic fields in the star formation process and bring together the latest observations with the latest theories to see what progress can now be made in addressing this question. The ordering of this Editorial follows the broad theme of observations followed by theory, with each scaling roughly from large scales to small—from entire molecular clouds to individual protostars.

Crutcher and Kemball begin the observation section with a discussion of the use of the Zeeman Effect to measure the line-of-sight strength of magnetic fields in molecular clouds and the general inter-stellar medium (ISM). This has only been detected in three species in the general ISM, HI, OH and CN, and in three species in masers, OH, CH<sub>3</sub>OH, and H<sub>2</sub>O. The Zeeman Effect calculates the line-of-sight field strength from measurements of the hyper-fine splitting of a degenerate line, where the amount of splitting is directly proportional to the field strength, with the constant of proportionality relating to the Bohr magneton. The magnetic field strength can then be used to derive the mass to magnetic flux ratio to determine whether a cloud is magnetically super-critical (prone to collapse) or sub-critical (supported by the magnetic field) using a version of the magnetic virial theorem. The magnetic field strength shows a behavior with respect to the column density as follows (see their Figures 4, 5): below a column density of order 10<sup>21–22</sup> cm<sup>-2</sup> the field is essentially independent of column density (at around 10–20 μG); above this column density the field strength increases with increasing column density (with a relation of  $B \propto n^{0.65}$ ). In terms of volume density this transition occurs at roughly 300 cm<sup>-3</sup>. This can be interpreted in a way that says that low-density gas is sub-critical and high-density gas is super-critical.

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Pattle and Fissel move onto single-dish millimeter and far-infrared observations. Here again the dominant source of polarization is thermal emission from partially aligned dust grains. They discuss the currently popular radiative alignment torque mechanism for grain alignment, and the causes of depolarization, such as decreasing alignment efficiency and changes in magnetic field geometry on scales smaller than the beam. They go on to describe various techniques for inferring magnetic field strengths from linear polarization measurements. The polarization can be used to infer the magnetic field strength most commonly via the DCF method, for comparison with the Zeeman measurements. Interestingly, a very similar result is seen (see their Figure 2) to that discussed above in the Crutcher and Kemball paper. In fact, the agreement between these totally different methods is quite striking, especially given that the Zeeman effect measures the line-of-sight magnetic field and polarization can only probe the plane-of-sky field. They discuss observations in a variety of environments, such as ionized regions, infrared-dark clouds, filaments, isolated globules and molecular cloud complexes. There appears to be growing evidence for bimodality in the alignment between fields and filaments, with the fields lying preferentially either parallel to, or perpendicular to filaments. The observations can be interpreted as either a magnetic field passing through a filament, or else as a magnetic field being helically wound around a filament until it runs virtually parallel to the filament. In the former case it would be predicted that the filament would fragment, while in the latter case the filament might be predicted to be longer-lived. Magnetic fields in more isolated cores are seen to typically lie at 30 degrees to the projected short axis of the core. This can be explained as an ensemble of tri-axial asymmetric ellipsoids with the magnetic field parallel to the shortest axis. Projection effects then statistically favor this projected offset.

Hull and Zhang round up the observations section by discussing interferometric observations of magnetic fields in star-forming regions. Clearly, these observations cover the smallest scales currently observable, of protostars and their circum-stellar discs at resolutions of 100 au or less in nearby regions. The polarization observed by interferometers at millimeter wavelength scale is dominated by preferential thermal emission from partially aligned dust grains. Field strengths are estimated from these observations to be in the region of fractions of a mGauss to a few mGauss. The authors claim that the most recent observations appear to show that the popular quasi-static, magnetically-dominated core collapse model is an oversimplification in all but a few cases. This model produces the classic hour-glass field morphology, but it appears that only a few such cases are seen. The apparent random alignment of magnetic fields and outflows suggests that the fields do not determine the angular momentum direction during collapse. The small virial parameters seen in many cases also throw into question virialized collapse models, although the authors mention that strong fields could account for the low virial parameter.

Krumholz and Federrath begin the theory section by studying the effect of the magnetic field on the star formation rate (SFR) and the initial mass function (IMF) of stars. The authors claim that the most significant effects of the magnetic field on the

SFR are all indirect. They provide examples, including: magnetic fields provide support against gravitational collapse; they give additional support against shock compression, making it more difficult to shock gas to very high densities; it is also possible that magnetic fields inhibit the decay rate of the turbulence that is driven by the self-gravitational compression of the gas. They finish by looking at the effects of the magnetic field on the stellar IMF. They discuss the two-component IMF: log-normal plus power-law tail. The former comes from the general turbulence in the ISM generating a log-normal distribution of pre-stellar core masses, while the latter has been attributed to a linear scaling of post-shock gas density with shock Mach number. The authors claim that the latter effect does not match the observations after the introduction of magnetic fields. The authors themselves have made a series of models of MHD-turbulence-regulated star formation, using a Press-Schechter formalism, and claim to find better agreement with observations, such as the Salpeter power-law tail of the IMF.

Hennebelle and Inutsuka explore the role of magnetic fields in the formation and evolution of molecular clouds. They start from ideal MHD and incorporate the first non-ideal correction, namely ion-neutral drift. They return to the topic introduced observationally in an earlier chapter of magnetic fields and filaments, but this time consider the theoretical implications. They deduce that the magnetic field is probably responsible for shaping the inter-stellar gas by generating a multitude of filaments, and for reducing the overall star formation efficiency by a factor of a few. Furthermore, they could indirectly lower the star formation efficiency by a further factor by enhancing the stellar feedback in higher-mass stars.

Wurster and Li continue the theoretical section by considering magneto-hydrodynamic (MHD) simulations of protostellar discs. Velocity data indicate that typical pre-stellar cores have enough angular momentum to generate a protostellar disc of scale of order 100 au. However, what is not known is to what extent magnetic braking helps to dissipate this angular momentum and hence suppress disc formation. Ideal MHD simulations can prevent disc formation in some cases, although disks can form in the presence of turbulence, which leads to the misalignment of the field and the angular momentum. Theorists have turned to non-ideal MHD to salvage disc formation and form the hundreds of discs and thousands of planets that have been observed. Non-ideal MHD includes both charged and neutral species, allowing for a weakly-ionized ISM. Non-ideal processes help to diffuse and weaken the magnetic field, hence reducing the magnetic braking effect and allowing discs of sizes of tens of au to form. The authors find that by misaligning the B-field and angular momentum vectors, larger or smaller discs can form, depending on environmental conditions.

Pudritz and Ray move on from circum-stellar discs to protostellar outflows. Bipolar outflows are observed right across the stellar mass spectrum and are fundamental to the star formation process. They are one of the key processes invoked to inject turbulence into the ISM, as well as often being invoked to carry away excess angular momentum from collapsing protostars. Observations now confirm that the jets at the centers of outflows do, in fact, rotate. Of the two main theoretical outflow

launching mechanisms that have been proposed, the magneto-rotational instability (MRI) turbulence model has recently run into problems relating to damping, and so the authors claim that the magnetized disc wind model is the more likely to transport angular momentum from the disc to the jet and explain the observations of rotating jets. Recent multi-scale MHD observations can now trace star formation evolution from giant molecular cloud (GMC) scales of tens of pc down to circumstellar disc scales of tens of au for the first time in a single code. The authors conclude that feedback from magnetized outflows plays a key role in regulating the star-formation efficiency of a molecular cloud.

Teyssier and Commerçon round up the volume by reviewing numerical schemes for MHD and radiation transfer for the modeling of star-formation regions in environments where the turbulence is both super-sonic and super-Alfvénic and include the effects of radiation and self-gravity. They describe the most popular types of numerical schemes: smoothed particle hydrodynamics (SPH); finite difference methods; and finite volume methods; including various implementations of non-ideal MHD effects; Ohmic and ambipolar diffusion, and the Hall Effect. They discuss how to overcome the major numerical problems both for SPH and grid methods: divergence-free magnetic fields; numerical diffusion; and resolution requirements. For the avoidance of infinitesimally small time-stepping, they discuss sink particles and sub-grid models, although these are not without their drawbacks. Multi-fluid, multi-phase approaches have recently been all but abandoned due to their prohibitive computational cost. They conclude that there is still much work to do, given that all existing models have been forced to cover only a limited portion of the full parameter space needed in this field.

Overall, this volume puts together all the many aspects of the role of magnetic fields in the formation of stars from

both observational and theoretical perspectives and presents the reader with numerous challenges and issues for future work in many different directions. It is hoped that proposed new instrumentation, such as SPICA-Pol and the new imaging polarimeter under construction for JCMT will continue to move this field forwards. Progress in this field touches on so many other areas of astrophysics, from planet formation, to the evolution of whole galaxies. Within the next decade it could be possible to determine the complete energy balance of entire disk galaxies.

## AUTHOR CONTRIBUTIONS

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