FM4 – Magnetic Fields along the Star-Formation Sequence

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Magnetic fields along the star-formation sequence: bridging polarization-sensitive views

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Abstract. It is believed that magnetic fields play important roles in the processes leading to the formation of stars and planets. Polarimetry from optical to centimeter wavelengths has been the most powerful observing technique to study magnetic fields: the development of polarimetric capabilities on a wide range of observational facilities now allows to probe the magnetic field properties in various objects along the star formation sequence, from star-forming molecular clouds to young stars and their protoplanetary disks. However, the complexity of combining results from different observational techniques and facilities emphasizes the need to transcend historical barriers and bring together the various communities working with polarimetric observations. This Focus Meeting was a first step to compare observations of magnetic fields at the various evolutionary stages and physical scales involved in star formation processes, such that we can establish a coherent view of their key role in the multi-scale process of star formation.

Keywords. magnetic fields, stars: formation, polarization, techniques: polarimetric

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Starting with a subtle interplay between gravity, turbulence, and magnetic fields during the formation of molecular clouds, the complexity of the star formation process is rooted in the conditions of the gas and the effectiveness of processes that remove angular momentum and magnetic flux, not just at the onset of gravitational instability but throughout the evolution of the forming star toward the zero-age main sequence (ZAMS). During the $\sim$1 million years needed to form a star, gravity has to overcome two main barriers to transform a dense core into a star: the dense core's angular momentum and its magnetic flux. The outcome of the collapse (manifested in the stellar mass function, occurrence and properties of protoplanetary disks, stellar multiplicity, etc.) depends critically on how and when these two barriers are surmounted. While the gas dynamics at most of the relevant scales ($0.1 - 10000$ au) are now accessible to observations, a thorough understanding of the star formation process will not be achieved until we have characterized the role of the magnetic field across all of the spatial and timescales relevant to the process of star formation. High-sensitivity, high-resolution polarization observations by new and planned next-generation facilities (ALMA; BLAST-TNG; HAWC+ on SOFIA; SCUBA-2 on JCMT; NIKA2 on the IRAM-30m; PolKa at APEX; CanariCam at the GTC; SPIROU on the CFHT; CRIRES+ on the VLT; PEPSI at the LBT; MIMIR and many others) are ushering in a new era in the study of polarized light, allowing us to uncover the properties of the magnetic field over a broad range of wavelengths and physical scales. Our Focus Meeting was built to gather the different communities studying magnetic field properties in objects along the evolutionary sequence leading to star formation, from molecular clouds to young stars reaching the ZAMS, and to identify synergies to compare, combine, and synthesize knowledge of the end-to-end role of the magnetic fields in the formation of stars. Can we establish a coherent picture of the role of the magnetic field in the star-formation sequence across time and spatial scale, in spite of the diverse observational techniques and analysis tools used to observe magnetic fields in molecular clouds, filaments, cores, young stars and their disks? We briefly summarize below the models and observations of magnetic fields at the various stages of the star-formation process that were shown and discussed at the meeting.

The initial setting for the formation of stars takes place in dense filamentary structures within molecular clouds. Observations of the Zeeman effect from molecular lines emission have revealed magnetic fields at the ∼parsec scale in nearly all star-forming clouds (which have typical densities $100 - 10^4$ cm^{-3}) . Recent results from the polarized dust emission observed with *Planck* have confirmed the ubiquity of magnetic fields at molecular-cloud scales, showing that the orientation of the magnetic field is mostly parallel to diffuse filamentary structures in the ISM, whereas the field tends to be perpendicular to the dense, self-gravitating structures where star formation takes place. The comparison of these observations with numerical simulations of magnetohydrodynamic (MHD) turbulence suggests a rough equipartition between magnetic and turbulent kinetic energies, and a key role of magnetic fields in the evolution and fate of star-forming material in molecular clouds. However, even along the same line of sight, different wavelengths probe different density regimes, and both line-of-sight and plane-of-sky depolarization effects can affect the determination of the magnetic field orientation.

Once ∼0.1 pc dense cores (which have typical densities $10^3 - 10^6$ cm^{-3}) are formed from the fragmentation of molecular cloud material, they can remain gravitationally stable or undergo collapse to form one or several stellar embryos. Both starless cores and protostellar cores actively forming stars show polarized dust emission in the (sub)millimeter domain, suggesting magnetic field strengths of $\sim 10 - 1000\,\mu$G. New polarimetric capabilities at various observatories will allow us to estimate the energy budgets of gravity, turbulence, rotation and magnetic fields in star-forming cores, thereby characterizing the physical processes contributing to the ability (or inability) of dense cores to form stars. During the meeting, new sensitive observations covering multiple scales were presented; however it is still unclear whether the magnetic field is retained from the filamentary clouds during core formation, and how important the field is for physically supporting the cores. Large-scale surveys with future space observatories (SPICA, OST) that would probe the magnetic field structure with sensitivity and spatial dynamic ranges comparable to those achieved by, e.g., *Herschel* images of the cold ISM in unpolarized emission, will be key to address this question.

A stellar embryo evolves by accreting material from the parent core, and moves through the protostellar and pre-main-sequence stages until the resulting star finally arrives on the main sequence. One of the major challenges for the formation of stars is the "angular momentum problem": observations show that, over the course of the ∼100,000 yr that it is being accreted onto the stellar embryo, the material in the protostellar core needs to reduce its specific angular momentum by 5 to 10 orders of magnitude. While the formation of multiple systems, disks, jets and outflows may help remove excess angular momentum, these processes seem unable to fully solve the problem during the short ($< 10^5$ yrs) main accretion phase. Analytical models and MHD numerical simulations of the evolution of star-forming cores show that the magnetic field is critical for transporting angular momentum during the protostellar phase: characterizing the efficiency of magnetic braking during the main accretion phase is therefore of utmost importance.

Moreover, MHD models suggest that the magnetic field is a key player in the formation of massive stars, because the field increases the gravitational stability of massive cores – the seeds of massive stars – and also sets the conditions for strongly anisotropic accretion of the surrounding material, ultimately permitting more mass to be accreted. While observations of the polarized dust continuum emission with both high dynamic range and angular resolution (e.g., with ALMA) have started providing constraints on magnetic models of protostellar collapse, new challenges are emerging to probe the magnetic field properties in the very high density regimes where the dust thermal emission at sub-mm wavelengths becomes optically thick. The meeting gathered communities working on polarization observations, as well as experts from dust modeling, who discussed how to best characterize the properties of magnetic fields at high densities where their effect on the angular momentum evolution during the protostellar stage might be crucial to describe the formation of stars and disks.

Regarding the late evolutionary stages of the star formation process, high-spectral-resolution circular spectropolarimetry of pre-main-sequence (PMS) stars and their circumstellar environments (which have typical densities $10^{10} - 10^{30}$ cm^{-3}) reveals strong kGauss fields in these T Tauri objects. Their properties suggest some of the parental core magnetic conditions ("fossil fields") remain, in addition to the fields generated by the stellar dynamo. Moreover, observations of young stars of intermediate mass (> 1.4 $M_\odot$: Herbig Ae/Be stars) have shown evidence for large-scale organized magnetic fields, suggesting that the magnetic structure of these stars could be partly due to compression of the pristine magnetic fields during the early phase of the star-formation process. Characterizing the connection of the magnetic field between the PMS star and the inner part of its disk is also key to understand the evolution of young stars. Indeed, not only are these magnetic field lines thought to be the dominant pathway for accretion during the PMS stage ("magnetospheric accretion"), but the role of the field in controlling the evolution of angular momentum of the star might be paramount for slowing the rotation of young stars prior to their arrival on the main sequence. Future studies should pave the way towards a global picture of magnetospheric accretion processes over the whole stellar-mass range. We discussed how the synergy of new observing techniques now makes it possible to investigate how much of the initial magnetic field survives the star formation process, and whether the resulting field in young stars strongly depends on the properties of the parent core. Finally, we briefly discussed how our efforts to account for the diversity of exoplanetary systems must comprise a deeper understanding of the interaction between stellar magnetic fields and the protoplanetary disks: if magnetic fields affect the structure and evolution of disks, then planet formation and migration could be greatly affected by magnetic conditions during star formation.

In summary, the magnetic field is omnipresent at all scales and stages of star formation, and thus drives several key processes during the formation of stars such as (1) removing angular momentum during the main accretion phase, (2) affecting disk initial conditions and subsequent planet formation, (3) allowing late-stage accretion onto PMS stars, and possibly even (4) braking the newly born stars themselves through star-disk interaction. However, magnetic fields remain difficult to observe since they can rarely be observed directly; rather, we mostly rely on observations of polarized emission from dust and spectral lines, both of which have significant limitations. Very diverse observational techniques and analysis tools must be used to probe magnetic fields in the different types of star-forming objects: only by bringing together communities studying magnetic fields in molecular clouds, star-forming cores, protostars, disks, and PMS stars, can we overcome the current limitations and ultimately move synergistically toward a coherent picture of the role and evolution of magnetic fields in the star formation process.