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Concluding Remarks: Magnetic Coronae in an Astrophysical Context

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Abstract. Magnetic coronae are found not only on the Sun and solar-like stars, but also on disk-surrounded young stellar objects, perhaps around some high-mass stars, and on accretion disks around young stars, galactic compact objects, and active galactic nuclei. Coronae point to the operation of dynamos in many of these objects. Coronal magnetic fields are interesting laboratories for plasma physics, but they are also the origin of radiation that may fundamentally influence the stellar environment. This brief summary of the series of companion papers illustrates a number of recent achievements in coronal physics, but also discusses open questions where more investment is needed.

Key words. Stars: coronae – Accretion disks: coronae – Stars: accretion – Stars: magnetic fields

1. Introduction

Best known from the Sun, magnetic coronae are found in a surprisingly wide (and increasing) variety of astrophysical objects. Phenomenologically, the solar corona is the outer, thin atmosphere that is structured by magnetic fields anchored in the solar photosphere; the fields are generated by the magnetic dynamo at the interface between the radiative core and the convective envelope. These same magnetic fields also carry energy tapped from the convective motion of the photosphere, store them in non-potential field configurations in the corona, and eventually release the energy in violent reconnection events, heating plasma to millions of degrees and accelerating particles. Coronae of the solar type operate in such a way that the driver of the magnetic-field motion is located in a high-plasma beta region (the photosphere) where gas motion guides magnetic fields, while the energy-release region is in a low-plasma beta environment, where the magnetic forces dominate.

Such configurations may be found in a variety of astrophysical objects. Solar-type coronae have been identified on essentially all classes of cool stars (except for some cool giants) including pre-main sequence stars at least back to the Class-I stage. Magnetized outer atmospheres may be present - somewhat unexpectedly - around hot stars with winds as well. But the analogy goes further. Accretion disks may produce their own disk coronae, perhaps again driven by a dynamo, and such structures are found around pre-main sequence stars, X-ray binaries, and active galactic nuclei. In accreting systems, a chain of further mechanisms is driven by the magnetic fields, such as accretion onto the central object, mass loss in winds, outflows and jets, and stellar spin-down through transfer of angular momentum.

Much of the relevant physics has been treated only in very simplified ways. As the associated collection of papers shows, coronal research is in a lively state of evolution. Summarizing all aspects is out of reach, but giving a taste of what is under debate may be possible. The following sections address some key issues discussed in the paper series, and a selection of open issues regarded to be important for future research.

2. Coronal origin: Dynamos

The standard solar $\alpha\Omega$ dynamo model locates the magnetic-field production in the tachocline near the bottom of the convection zone. Unstable flux loops will buoyantly rise to the surface. The flux rising is strongly influenced by the ratio between magnetic buoyancy and Coriolis forces that themselves increase with the stellar rotation rate; these forces and the size of the radiative core will determine where magnetic fields erupt; latitudes of field emergence will increase with stellar rotation rate, with decreasing stellar mass and with earlier evolutionary stage (Holzwarth 2007).

These scenarios can now be explicitly tested thanks to sensitive Doppler imaging of magnetic surface features (Strassmeier et al. 2007; Jardine 2007; Berdyugina 2007). Although still challenging for general applications, these methods have given evidence of "polar spots"; very large features have been identified on several magnetically active stars. Zeeman Doppler Imaging takes surface mapping one step further as sensible extrapolations to coronal regions become possible (Jardine 2007; see below).

A solar-like dynamo should not operate in fully convective stars, yet such stars are sources of strong X-rays, in particular in the pre-main sequence domain. There does not seem to be a dependence between coronal emission and rotation rate in T Tauri stars, although their longer convective turnover time may simply shift these stars into a saturation regime as seen on main-sequence stars. However, the missing convective boundary strongly suggests that a different dynamo is in operation, such as a turbulent dynamo. Such a (non-dominant) dynamo may be operational in the Sun as well (Preibisch 2007).

New, hitherto unrecognized dynamo modes may have to be considered. Stable, active longitudes and flip-flop cycles (periodic switching of dominant spot production between two active longitudes) point to the presence of non-axisymmetric dynamo modes (Berdyugina 2007). The "Rieger" cycles seen in high-energy flares both on the Sun and on stars may be rooted in stellar interiors as well, but the physics leading to them remains to be identified (Massi 2007).

Selected open problems: How do dynamos operate, in convective/radiative stars, in fully convective stars, in thin accretion disks? What determines the operation of non-axisymmetric dynamo modes? Observationally, fully convective stars (very low-mass and pre-main sequence stars) should be systematically mapped repeatedly over long time scales, using Doppler imaging.

3. Coronal energy release: Reconnection

Magnetic fields above their anchor surfaces (e.g., stellar photospheres or disks) are prone to magnetic reconnection that transform magnetic energy rapidly into heat, motion, and accelerated particles. It is perhaps interesting to note that during solar minimum, the entire coronal magnetic connections change on time scales of only about one hour! Although textbook arrangements of reconnecting magnetic fields may look simple, the actual configurations developing even for simple starting conditions are rather complex; various interaction surfaces and -lines between opposite polarities have to be considered where reconnection most likely develops. It is important that these calculations be performed in 3-D, leading to faster but longer heating processes (Parnell 2007).

The complexity of coronal reconnection in solar flares is evident from spatially resolved observations. Although many observations support the standard scenario (reconnection in high corona - particle acceleration -

footpoint heating - evaporation - X-ray emission), there are numerous features that defy an explanation in the picture of simplified "cartoon models". A most crucial question is on triggers that launch flares (Harra 2007).

Efforts to simulate heating processes have encountered the problem of very large ranges of time scales (from time scales of thermal conduction to the life time of active regions) and spatial scales (from the dissipation length scale of a few meters to the scale of solar active regions) to be considered simultaneously. There is no lack of energy in the photosphere to explain all coronal output, and new DC heating models in fact reproduce coronal loop structure, coronal temperatures, involved gas masses, and the differential emission measure distribution (Gudiksen 2007). How the energy release proceeds in detail is difficult to infer from such models, but magnetic dissipation is most likely occurring in many nanoflare events.

In large-scale magnetic fields around young stars, and in particular around binary systems, new reconnecting configurations can lead to extremely powerful energy release. Evidence for interacting "helmet-streamers" has been found in T Tauri binaries, leading to quasi-cyclic flares (Massi 2007).

Selected open problems: Realistic simulations of large-scale coronal features (active regions) in 3-D are required. On the other hand, plasma-physical processes of particle acceleration and heating must be connected with MHD. Multi-wavelength observations of the solar corona at high spatial resolution should be important. Imaging at relatively high energies relevant for flares may be useful to pin down particle acceleration and heating physics (now partly available from Hinode). Explicit measurement of vector magnetic fields across active regions is a challenging goal.

4. Coronal environments: Disks, jets

Extrapolation of magnetic fields of disk-surrounded T Tauri stars inevitably leads to the question of star-disk interactions. While this problem has often been treated "the wrong way around", starting with required conditions at the truncation radius of the disk and extrapolating to the stellar surface, Zeeman Doppler Imaging now provides good diagnostics to actually model these magnetic fields. Coronae of lower-mass stars in particular will reach out to the corotation radius (Jardine 2007).

How does the corona interact with its disk environment? On the one hand, there are claims that accretion streams produce additional, soft X-ray sources when forming shocks on stellar surfaces (Montmerle 2007; Preibisch 2007; Güdel 2007); on the other hand, accretion streams are also excellent cooling agents, and they have been proposed to be responsible for the X-ray deficiency of coronae of accreting T Tauri stars (Preibisch 2007; Güdel 2007). The dominant high-energy emission from T Tauri stars is, however, thought to originate in a solar-like corona (Preibisch 2007).

Star-disk magnetic fields may be efficient in locking the stellar rotation period to the inner-disk orbital period. However, simplified models may not apply; measured magnetic field strengths are indeed too small (Jardine 2007), and in fact disk-locking and accretion are contradictory requirements (Ferreira & Zanni 2007). Stellar spin-down may be easier to achieve by stellar winds flowing along open field lines, or by loading disk material onto open field lines anchored on the star (Ferreira & Zanni 2007).

Where the disk fields originate is unclear; accretion could drag them in from the envelope, but disk dynamos may generate their own magnetic coronae in which fields can reconnect; simulations assuming different magnetic polarities (of disk/stellar fields) show how disk winds/outflows may form (Brandenburg & von Rekowski 2007; Ferreira & Zanni 2007; Malzac 2007). A disk corona may itself be the origin of the jets around compact objects (Malzac 2007).

Selected open problems: The interaction between stellar magnetic fields and the innermost region of accretion disks is of crucial interest to understand jet formation, accretion physics, and stellar spin-down. Detailed magnetospheric models, based on surface imaging of T Tauri stars, should be constructed. What are the magnetic fields on accretion disks, theoretically from modeling and observationally? What is the stability of accretion disks and the ejected jets in the presence of magnetic fields?

5. Coronae in a bigger picture

While the field of coronal physics has enjoyed extremely important progress, coronal research has to stand the question on “justification”. Is coronal research relevant outside the very field of coronal magnetic fields, regardless on what type of object they occur? The answer is a clear “yes”. Coronae, and specifically the solar corona, have provided the key to our modeling of cosmic magnetic reconnection, particle acceleration and plasma heating. Similar physics is relevant for a variety of cosmic objects, among them the terrestrial magnetosphere with its plethora of high-energy processes; “coronal” mechanisms (dynamos, turbulence, particle acceleration, reconnection) may also occur on large galactic scales.

Coronae are similarly relevant for cross-disciplinary studies. The high-energy radiation, energetic particles, and the solar wind originating from various “coronal” processes are primary drivers of evaporation of outer planetary atmospheres (e.g., Chassefière & Leblanc 2004). While this is true in the present-day solar system, the much elevated radiation in the young solar system may in fact have been responsible for the escape of water from Venus, and for the escape of much of the atmosphere of Mars. At younger ages, X-rays from pre-main sequence stars irradiate accretion disks, heat their upper layers, and ionize the gas. Chemical networks may be driven, and the magnetorotational instability may set in if ionized disk material encounters magnetic fields. Planet formation may meanwhile occur in the innermost, quiet disk layers (e.g., Glassgold et al. 2004). Solar short-wavelength radiation may well have been a driver of important chemistry in the young terrestrial atmosphere (e.g., Canuto et al. 1982) and therefore - eventually - for the formation of life. There is no reason not to emphasize such apparently outlying “applications” of coronal physics!

6. A last word

The above brief summary has highlighted only a selected sample of results and questions. Numerous discussions and poster papers have contributed much more than fits on these four pages, further showing that coronal physics is a lively field of research. A most lasting impression from the conference may, however, have been the wide recognition of the “complexity” of coronal magnetic fields. Cartoon models are widespread in discussions of coronal flares, star-disk accretion processes, reconnection physics, jet acceleration above accretion disks. They help setting the stage for further concepts, but as various papers have clearly shown, they fail more often than not once the true observations are studied. Magnetic fields in coronae are complex, dynamic, and difficult to model. This is a sign of a mature science. We should not be shy to accept the challenges.

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