TIME DEPENDENT MAGNETOSPHERIC ACCRETION IN T TAURI STARS

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Abstract. We review recent observational results which suggest that magnetically channeled accretion in T Tauri stars is a highly time dependent process on timescales ranging from hours to months.

Keywords: T Tauri stars, magnetospheric accretion

1. Introduction

T Tauri stars are low-mass stars with an age of a few million years, still contracting down their Hayashi tracks towards the main sequence. Many of them, the so-called classical T Tauri stars, show signs of accretion from a circumstellar disk (see, e.g., Ménard and Bertout, 1999 for a review). Surface magnetic fields of order of 1–3 kG have recently been derived from Zeeman broadening measurements (Johns Krull et al., 1999, 2001; Guenther et al., 1999) as well as from the detection of electron cyclotron maser emission (Smith et al., 2003). These strong stellar magnetic fields are believed to alter significantly the accretion flow in the circumstellar disk close to the central star. Based on models originally developed for magnetized compact objects in cataclysmic binaries (Ghosh and Lamb, 1979) and *assuming* that T Tauri magnetospheres are predominantly dipolar on the large scale, Camenzind (1990) and Königl (1991) showed that the inner accretion disk is expected to be truncated by the magnetosphere at a distance of a few stellar radii above the stellar surface for typical mass accretion rates of 10^{-9} to $10^{-7} M_{\odot}\mathrm{yr}^{-1}$ in the disk (Basri and Bertout, 1989; Hartigan et al., 1995; Gullbring et al., 1998). Disk material is then channeled from the disk inner edge onto the star along the magnetic field lines, thus giving rise to magnetospheric accretion columns. As the free falling material in the funnel flow eventually hits the stellar surface, accretion shocks develop near the magnetic poles. The successes and limits of static magnetospheric accretion models (MAMs) in accounting for the observed properties of classical T Tauri systems (CTTS) have been reviewed by Bouvier, Alencar and Dougados (2003). We discuss here recent results which suggest that the interaction between the star's magnetosphere and the inner disk is a highly dynamical and time dependent process.

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2. Magnetospheric Accretion : A Dynamical Process

Evidence for magnetically mediated accretion mostly comes from snapshot studies and it is only recently that the stability of the phenomenon has started to be thoroughly investigated. In this section, we briefly review model predictions regarding the temporal evolution of the process (a more detailed account is given by Uzdensky, this volume) and recent observational results which indicate that it is highly time dependent indeed.

2.1. Time dependent models

Most MAMs assume that the stellar magnetosphere truncates the disk close to the corotation radius, i.e., the radius in the disk where the Keplerian angular velocity of the disk material equals that of the star. Field lines threading the disk at this radius thus corotate with the central object. However, due to the finite radial distance over which the stellar magnetosphere interacts with the inner disk, the footpoints of most field lines rotate differentially, one being anchored into the star, the other into the Keplerian disk.

Recent numerical simulations indicate that magnetic field lines are thus substantially distorted by differential rotation on a timescale of only a few Keplerian periods at the inner disk. One class of models predict that differential rotation leads to the expansion of the field lines, their opening and eventually their reconnection which restores the initial (assumed dipolar) magnetospheric configuration (e.g. Aly and Kuijpers, 1990; Goodson et al., 1997; Goodson and Winglee, 1999; Uzdensky et al., 2002). Magnetospheric *inflation cycles* are thus expected to develop and to be accompanied by violent episodic outflows as field lines open and reconnect as well as time dependent accretion rate onto the star (Hayashi et al., 1996; Romanova et al., 2002). The most recent 3D MHD simulations of disk accretion onto an inclined stellar magnetosphere are presented in Romanova et al. (2003) and illustrate well the extreme complexity of the process.

Other models, however, suggest that the field lines respond to differential rotation by drifting radially outwards in the disk, leading to magnetic flux expulsion (Bardou and Heyvaerts, 1996). The response of the magnetic configuration to differential rotation mainly depends upon the magnitude of magnetic diffusivity in the disk, a parameter of the models which is poorly constrained from first principles.

2.2. Observational evidence for time dependent magnetospheric accretion

Spectrophotometric monitoring studies of CTTS have brought clues to a time dependent interaction between the inner disk and the stellar magnetosphere. Thus, episodic high velocity outbursts, possibly connected with magnetospheric reconnection events, have been reported for a few systems based on the slowly varying velocity of blueshifted absorption components in emission line profiles on a timescale of hours to days (Alencar et al., 2001; Ardila et al., 2002). Possible evidence for magnetic field lines being twisted by differential rotation has also been reported for SU Aur by Oliveira et al. (2000). These authors measured a time delay of a few hours between the appearance of high velocity redshifted absorption components in line profiles formed at different altitudes in the accretion column. They interpreted this result as the crossing of an azimuthally twisted accretion column on the line of sight. Another possible evidence for magnetic field lines being twisted by differential rotation and leading to quasi-periodic reconnection processes has been reported for the embedded protostellar source YLW 15 based on the observations of quasi-periodic x-ray flaring (Montmerle et al., 2000).

Synoptic studies lasting for several weeks were performed for a handful of CTTS and provide new insight into the magnetospheric accretion process and its temporal evolution. Two of these have targeted the CTTS AA, Tau, which proved to be ideally suited to probe the inner few 0.01 AU of the disk-magnetosphere interaction region. Due to its high inclination ($i \simeq 75^{\circ}$, see Bouvier et al., 1999), the line of sight to the star intersects the region where the stellar magnetosphere threads the inner disk. The peculiar orientation of this otherwise typical CTTS maximizes the variability induced by the modulation of the magnetospheric structure and thus provides the strongest constraints on the inner disk and the magnetospheric cavity.

A first monitoring campaign (Bouvier et al., 1999), led to the discovery of recurrent eclipses of the central object with a period of 8.2 days. The eclipses were attributed to a nonaxisymmetric warp of the inner disk edge, located at about 8 $R_{\star}$, which periodically obscures the central star as it orbits it at Keplerian speed. Such an inner disk warp is expected to develop as the disk encounters an *inclined* magnetosphere (Terquem and Papaloizou, 2000; Lai, 1999; Romanova et al., 2003).

A second campaign combined photometry and high resolution spectroscopy (Bouvier et al., 2003). Spectroscopic variability yielded evidence for accretion columns and accretion shocks with their respective signatures (redshifted absorptions, continuum excesses) being modulated on a rotation timescale. Furthermore, a time delay of about one day was found between the flux variations of lines forming at different altitudes in the accretion column, from H_{α} near the disk inner edge to HeI close to the accretion shock at the stellar surface. The measured time delay is consistent with nonstationary accretion propagating downwards the accretion columns at free fall velocity, starting from a distance of about 8 $R_{\star}$, the radius at which the stellar magnetosphere disrupts the inner disk.

Over longer timescales, of order of one month, significant variations were also observed in the line and continuum excess flux, indicative of a smoothly varying mass accretion rate onto the star. Simultaneously, a tight correlation was found between the radial velocity of the blueshifted and redshifted absorption components in the H_{α} emission line profile (Figure 1). Since the former is a wind diagnostics while the latter forms in the accretion flow, this correlation provides additional evidence for a physical connection between (time dependent) inflow and outflow in

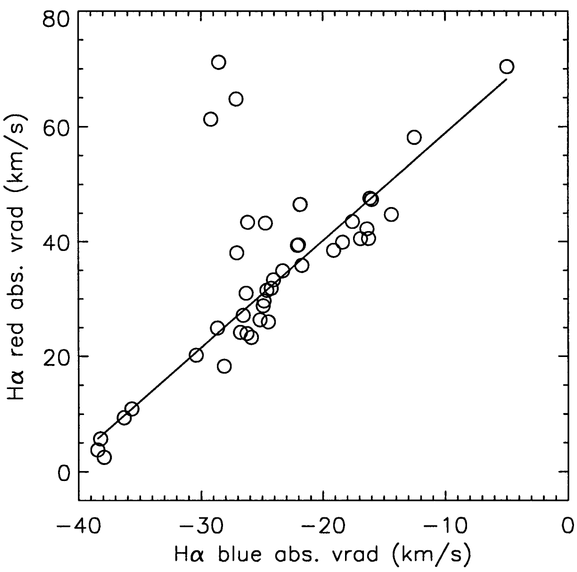

Figure 1. The correlation between the radial velocity of the blueshifted and redshifted absorption components in the H_α emission line profile of AA Tau (from Bouvier et al., 2003).

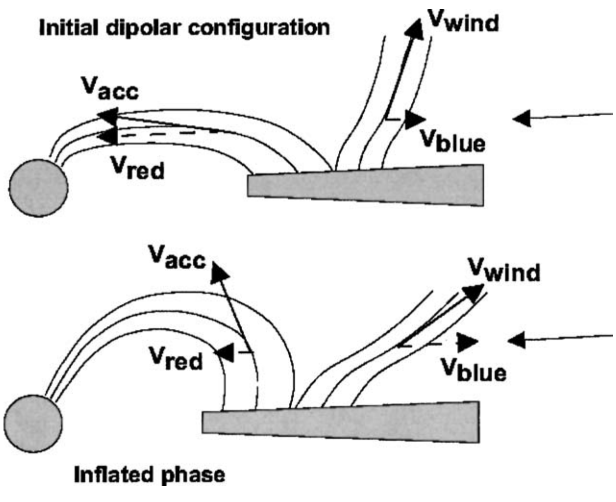

Figure 2. A sketch of the magnetospheric inflation scenario. The arrow on the right side indicates the line of sight to the AA Tau system (from Bouvier et al., 2003).

CTTS. Bouvier et al. (2003) argued that these flux and radial velocity variations can be consistently interpreted in the framework of *magnetospheric inflation cycles*, as predicted by recent numerical simulations of the star-disk interaction.

This is schematically illustrated in Figure 2. As magnetic field lines expand due to differential rotation between the star and the inner disk, the radial velocity of the accretion (resp. wind) flow decreases (resp. increases) due to projection effects on the line of sight, thus resulting in the observed correlation between the velocities of redshifted and blueshifted H_α absorptions (Figure 1) as the magnetosphere inflates. At the same time, the loading of disk material onto inflated field lines becomes increasingly difficult owing to the large angle field lines make relative to the disk plane. This results in a reduced accretion rate onto the star, as deduced from the depressed line and continuum fluxes observed at this phase (see Bouvier et al., 2003).

The last synoptic campaign on AA Tau thus yields the first evidence for global instabilities developping on a timescale of a month in the large scale magnetosphere, a result which yields support to the predictions of time dependent models of magnetospheric accretion. Whether these magnetospheric instabilities are truly cyclic, being driven by differential rotation between the star and the inner disk, as predicted by numerical models, will require additional monitoring lasting for several months.

3. Conclusion

Observational evidence for magnetospheric accretion being instrumental in classical T Tauri stars has accumulated in recent years. Several key properties of these young stars are naturally accounted for by assuming that the stellar magnetic field governs the accretion flow close to the star. The strong variability of CTTS on all timescales, from hours to months (and possibly years, Bertout, 2000), further suggests that the magnetically mediated interaction between the accretion disk and the central object is a highly dynamical and time dependent process.

The implications of the nonsteadiness of magnetospheric accretion in CTTS are plentiful and remain to be fully explored. They range from the evolution of their angular momentum (Agapitou and Papaloizou, 2000), the origin of inflow/ouflow short term variability (Woitas et al., 2002, Lopez-Martin et al., 2003), the modeling of the near infrared excess of CTTS and of its variations both of which will be affected by a nonstandard and time dependent inner disk structure (Carpenter et al., 2001; Eiroa et al., 2002; Johns-Krull and Valenti, 2003), the origin of CTTS variability which is expected to be a complex combination of modulation by hot and cold spots and variable circumstellar extinction (e.g. DeWarf et al., 2003), and possibly the halting of planet migration close to the star (Lin et al., 1996).

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