Alfvén Waves in Disks, Outflows and Jets

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Abstract

Observations of young stellar objects, such as classical T Tauri stars (CTTSs), show evidence of accretion disks (ADs), outflows and jets. It is shown that Alfvén waves (AWs) are important in all of these phenomena. AWs can be created by turbulence in the AD and magnetosphere of a CTTS. Jets, stellar outflows, and the heating of the central regions of ADs may be due to the damping of AWs. Our recent investigations of the heating of the AD and the magnetosphere by AWs as well as of the structures produced in outflows from ADs initiated by turbulent AWs, are discussed. We comment on the possible importance of AWs in resolving the energy and angular momentum problems of CTTSs.

1 Introduction

The current picture of a classical T Tauri star (CTTS) is that of a central protostar, surrounded by a thin accretion disk that was formed as the result of the collapse of matter in a molecular cloud. At the corotation radius, the disk

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is disrupted due to the star’s dipole magnetic field. The accreting matter then follows the star’s magnetic field lines until it impacts on the stellar surface. This magnetospheric model accounts for the observational signatures seen in CTTSs, such as the excess of optical and ultraviolet continuum flux (veiling) and redshift absorption features in the emission line profiles (inverse P Cygni profiles) (Muzerolle, Hartmann, & Calvet 1998; Hartmann, Hewitt, & Calvet 1994). CTTSs display both outflow and inflow signatures (see, e.g., Edwards, Ray, & Mundt 1993).

Magnetic field lines on the order of 1 kG at the surface of the protostar are sufficient to disrupt the disk. The existence of magnetic fields of this magnitude on the star’s surface is inferred from observations (Johns-Krull et al. 1999; Guenther et al. 1999). Coupling of the accreting matter to the star’s magnetic field lines is possible if the temperature of the disk at the truncation radius is \( > 10^3 \) K, at which collisional ionization of metal ions comes into effect (Umebayashi & Nakano 1988).

A major problem to be resolved concerns the gravitational energy \( E_G \) of the accreted matter, which is over an order of magnitude greater than the emitted energy \( E_\ast = \bar{L}_\ast \tau_\ast \) of the CTTS, where \( \bar{L}_\ast \) is the average optical luminosity and \( \tau_\ast \) is its lifetime. It has been suggested that the occurrence of large ejections could possibly get rid of the excess gravitational energy, but no detailed analysis has been made so far.

Another problem that must be dealt with is the large amount of angular momentum loss required for the formation of a protostar in a CTTS. The average protostellar mass \( M_\ast \) in a molecular cloud has an angular momentum 4-5 orders of magnitude greater than a protostar in a CTTS. It has been suggested that the Balbus and Hawley Instability (BHI) (Balbus & Hawley 1991, 1998) in the accretion disk may be able to get rid of the excess angular momentum. Detailed calculations of this possibility have yet to be made, although it has been shown in 3D numerical simulations that angular momentum can, in fact, be transported outward in the disk by the BHI (Hawley & Stone 1998).

Energy and angular momentum in CTTSs can be transported over large distances by Alfven waves which are generated by perturbations of the magnetic field, embedded in the plasma of the protostar. In general, AWs are weakly damped, as compared with sonic waves. The wave transports the energy and angular momentum away from the source of the perturbation, generally turbulence, along the magnetic field lines at the Alfven velocity.
Classical plasma processes do not allow for accretion to take place in a disk. It is, thus, generally assumed that turbulence exists in the disk, in order to produce the anomalous viscosity required for accretion. This assumption justifies the existence of AWs in the disk.

AWs have indeed been observed in a space physics environment, in particular, the solar wind. Near the sun, most of the fluctuations observed are propagating outwards (Bavassano 1990). Tu, Marsch and Thieme (1989) and Tu, Marsch and Rosenbauer (1990) found that, at a distance $\sim 64R_\odot$ from the sun, the fluctuations are outward-going with periods of $\sim$ minutes to days. All of the observations indicate that these fluctuations are, in fact, AWs. The waves are observed to have a power law distribution. Jatenco-Pereira, Opher and Yamamoto (1994) showed that the observed AW flux can explain the observed velocity of the solar wind as well as the observed radial temperature distribution in the corona and chromosphere. In the calculations of Jatenco-Pereiro et al. (1994), the network heating of Parker (1991) with a flux of $8.7 \times 10^5$ ergs cm$^{-2}$ s$^{-1}$, which has a damping length of $0.5 R_\odot$, was used. An Alfven flux of $1.3 \times 10^5$ ergs cm$^{-2}$ s$^{-1}$ was found to be necessary in order to fit the observed data. A coronal hole geometry, in which surface Alfven damping (Lee and Roberts 1986, Hasegawa and Uberoi 1982) at the border was assumed, was studied. The calculations predicted a spectral break at $10^{-2}$ Hz for a distance of $64R_\odot$, as is observed. This Alfven flux produced a $\sim 600$ kms$^{-1}$ wind, as is also observed.

In Section 2, our recent work on AW heating of the accretion disk and magnetosphere of CTTSs is presented. The structures produced in outflows from accretion disks, initiated by turbulent AWs, are treated in Section 3. Concluding remarks and a discussion of the energy and angular momentum problems in CTTS are given in Section 4.

2 AW heating in the accretion disk and magnetosphere of a CTTS

Accretion in the disk about a CTTS is generally assumed to be due to the BHI. An ionized plasma is required in order for the BHI to occur. However, Gammie (1996) predicted that the accretion disk is unionized in its central region from 0.1 to 5 AU. Based on the evidence by Stone et al. (1996) that
the BHI becomes turbulent, Vasconcelos, Jatenco-Pereira and Opher (2000) suggested that the BHI turbulence in the ionized regions produce AWs that propagate into the central region and heat it, so that the entire disk becomes ionized. They found that, assuming nonlinear mode coupling for the damping mechanism of an AW with a frequency 1/10 the ion cyclotron frequency, an AW amplitude of only 0.2% of the Alfven velocity was sufficient to create the necessary heating in the disk.

The required temperature profile of the magnetosphere, based on observations, was calculated by Hartmann, Hewitt and Calvet (1994). Martin (1996) studied the heating of the accreting matter as it follows the magnetic field lines in the magnetosphere. He took into account adiabatic compression, photoionization and ambipolar diffusion. He found too low a temperature for the magnetosphere due to these heating mechanisms and concluded that an additional heating source must be present. Vasconcelos, Jatenco-Pereira and Opher (2002) found that for an Alfven frequency of 1/10 the ion cyclotron frequency, an AW amplitude of only 0.3% the Alfven velocity was required to attain the necessary temperature.

3 Structures produced in the turbulent AW-initiated outflows from accretion disks

In a cold, non-turbulent disk, matter cannot leave the surface since it is bound gravitationally. A magnetic field perpendicular to the AD is generally assumed in CTTSs. Vitorino, Jatenco-Pereira and Opher (2002, 2003) studied the outflow from the accretion disk in a CTTS along the magnetic field lines, assuming, as did Ouyed and Pudritz (1997), that the corona of the disk is supported by a turbulent AW pressure $P_A$, taken to be $0.39P_{KR}$, where $P_{KR}$ is the Keplerian ram pressure, defined as $\rho V_K^2$, and $\rho$ and $V_K$ are the density in the disk and the Keplerian velocity, respectively. The $P_A$ balances the gravitational attractive force of the disk, allowing outflow to take place due to the centrifugal force. It is generally assumed that the twisting of the magnetic field lines due to the rotation of the disk will eventually transform the outflow into a jet.

Gas pressure in the corona $P_G$ was taken to be $0.01P_{KR}$. The initial poloidal magnetic field, perpendicular to the disk, was assumed to be $(8\pi P_G)^{1/2}$. 
It was assumed that the magnitude of the initial toroidal field was equal to that of the initial poloidal field, to which it was perpendicular. The density in the corona was taken to be $0.01\rho$.

The structure of the outflow after several hundred rotations of the inner Keplerian orbit was studied by Vitorino et al. (2002, 2003), using a 3D ZEUS code. Initially, they perturbed the outflow with a random velocity amplitude proportional to $r^{-a}$, where $r$ is the radius in the accretion disk and $a = -3/2, -1, -1/2, 0, 1/2$ and 1. The maximum random velocity perturbation at the inner orbit of the disk was 0.01 the Keplerian velocity. Although the perturbation was random, all the structures that formed had a spacing of 11 times the radius of the inner Keplerian orbit.

Periodic perturbations of the outflow were also studied by Vitorino et al. (2003). In this case, the structures that formed had a spacing of $T/2$ times the radius of the inner Keplerian orbit, where $T$ is the period of the perturbation. They investigated periods 10-80 times that of the inner Keplerian orbit $T_{Ki}$ and found that the structures dissipated for small $T (\sim 10 - 20T_{Ki})$ and tended to fragment for large $T (\sim 60 - 80T_{Ki})$.

It is to be noted that the investigations of Vitorino et al. (2000, 2003) are relevant for the formation of structures very near to the source, as yet unresolved with present telescopes. For example, the spacing of 11 times the radius of the inner Keplerian radius corresponds to a distance of only $\sim 10^{-6}$ pc.

### 4 Conclusions

In Section 2, it was shown that AWs may be important in ionizing the central unionized region of an AD of a CTTS, making it possible for the BHI to operate and accretion to take place. It was also shown in Section 2 that AWs may be important in raising the temperature of the magnetosphere of a CTTS, so that it agrees with observations. In Section 3, turbulent AW-initiated outflow from the disk was seen to create interesting structures.

Finally, I would like to comment on the energy and angular momentum problems with respect to CTTSs which were discussed in the introduction. Concerning the problem of the excess angular momentum, it is possible that it may be transported away from the disk by AWs instead of the BHI. As noted, AWs can transport energy and angular momentum over great dis-
tances along magnetic field lines. Moreover, turbulent AWs can not only initiate mass outflow, as discussed in Section 3, but can also carry angular momentum out of the disk, depositing it in the molecular cloud. Concerning the energy problem, the major portion of the gravitational energy of the accreted matter is lost when its distance to the protostar decreases from $\sim 3R_*$ to $\sim R_*$, where $R_*$ is the radius of the star. In the standard CTTS model, the accreting matter is found in the magnetosphere for radii $\leq 3R_*$. The presence of turbulence is assumed in the standard model for the accretion disk and we may assume that, due to the accreting matter, it is also present in the magnetosphere, where it can create large oscillations. In the region of the magnetosphere which touches the magnetic field lines that thread the disk, these oscillations can generate AWs. The AWs could transport appreciable energy outward from the magnetosphere into the molecular cloud.

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