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GLOBAL ALFVÉN WAVE HEATING OF THE MAGNETOSPHERE OF YOUNG STARS

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ABSTRACT

Excitation of a global Alfvén wave (GAW) is proposed as a viable mechanism to explain plasma heating in the magnetosphere of young stars. The wave and basic plasma parameters are compatible with the requirement that the dissipation length of GAWs be comparable to the distance between the shocked region at the star's surface and the truncation region in the accretion disk. A two-fluid magnetohydrodynamic plasma model is used in the analysis. A current-carrying filament along magnetic field lines acts as a waveguide for the GAWs. The current in the filament is driven by plasma waves along the magnetic field lines and/or by plasma crossing magnetic field lines in the truncated region of the disk of the accreting plasma. The conversion of a small fraction of the kinetic energy into GAW energy is sufficient to heat the plasma filament to observed temperatures.

Subject headings: accretion, accretion disks — MHD — plasmas — stars: magnetic fields — stars: pre–main-sequence

1. INTRODUCTION

In the present popular model for classical T Tauri stars (CTTSs), the so-called class II objects (Lada 1987), a central young star is surrounded by a geometrically thin accretion disk. The disk is disrupted at a given radius by the magnetic field of the star. For smaller radii the accretion flow follows the magnetic field lines of the star until it impacts onto the stellar surface (Ghosh & Lamb 1979; Königl 1991). This magnetospheric accretion model explains observational signatures seen in some CTTSs as, for example, the excess of optical and ultraviolet continuum flux (veiling), as well as redshift absorption features in emission line profiles (Muzerolle, Hartmann, & Calvet 1998; Hartmann, Hewett, & Calvet 1994). The plasma of the accretion disk flows along the dipole magnetic field lines toward the magnetic poles of the star. It is inhomogeneous in the plane perpendicular to the magnetic field lines, but although somewhat more homogeneous along the field lines, cavities and plasma condensations (plasmoids), aligned by the magnetic field, may be present. These plasmoids are distributed randomly in the plane perpendicular to the plasma flow. Waves excited by the shock of the plasma flux with the star's surface can propagate upstream and interact with the plasmoids, creating a current, which in turn, create current-carrying filaments. An upstream or downstream electric current can be driven by the waves or by the $\boldsymbol{v} \times \boldsymbol{B}$ MHD effect in the truncated region of the disk. Current driven by an electric field along a magnetic field is unstable to long-wavelength modes, such as the tearing instability, discussed by Mikhailovskii (1992) and Kadomtsev (1992), that can form filament structures along the magnetic field lines. Such filaments have been observed in the laboratory (see, e.g., Fadeev, Kvartskhava, & Komarov 1965; Rosenberg & Gekelman 2001). The occurrence of filaments has also been predicted in simulations of rotating magnetized disks (Machida, Hayashi, & Matsumoto 2000).

Hartmann et al. (1994) and, more recently, Muzerolle et al. (1998) carried out calculations on magnetosphere accretion models, solving the radiative transfer equations in the Sobolev approximation. Theoretical Balmer line profiles obtained were found to be in reasonable agreement with observations. The major uncertainty in radiative magnetosphere model calculations is the temperature profile along the tube. Martin (1996) calculated the temperature profile from the energy balance of the gas, including heating by adiabatic compression of magnetic field lines, Balmer photoionization, and ambipolar diffusion. However, the values of the temperature that he obtained were too low to explain the observed spectra. Thus, additional heating mechanisms inside the tube are needed.

The line-averaged electron temperature in the magnetosphere taken from optical measurements, is about 0.8 eV (see, e.g., Hartmann et al. 1994; Martin 1996; Muzerolle et al. 1998). Balancing the heating rate with the blackbody emission at a temperature $\approx$0.8 eV, we find that about 5% of the flux energy is sufficient to heat the downstream flux to a few eV. The main consumption of the flux energy is spent on plasma ionization. Using laboratory experimental data for the ionization-recombination processes (see Delcroix 1965), we can estimate the energy necessary for the plasma ionization rate to be about 50% in the filament for electron temperatures of about 1.6 eV. We use here a line averaged temperature profile, varying from $\sim$7500 to $\sim$8300 K, to reproduce the optical line features observed.

Taking into account the evidence for turbulence in the observations, as well as the necessity for an additional heating mechanism, Vasconcelos, Jatenco-Pereira, & Opher (2002) suggested that Alfvén waves may be important in the heating of magnetic flux tubes of CTTSs. They studied the possibility that the waves generated at the star's surface due to the shock are produced by the accreting matter, as suggested by Scheurwater & Kuijpers (1988).

Various damping mechanisms for Alfvén waves have been suggested in the literature, such as Alfvén resonant heating of solar loops (Hollweg 1990; Elfimov, de Azevedo, & de Assis 1996), wave damping by phase mixing (also in the solar context), and cyclotron heating, occurring as an Alfvén wave travels down a magnetic field gradient until its frequency

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matches that of the cyclotron resonance of helium or some other plasma specie due to the decreasing ion-cyclotron resonance (magnetic beach). In addition to the more conventional collisional and viscous-resistive Alfvén wave damping (Osterbrock 1961), Vasconcelos et al. (2002) concentrate on nonlinear and turbulent damping (Vasconcelos, Jatenco-Pereira, & Opher 2000). Nonlinear and turbulent damping have also been studied by Jatenco-Pereira & Opher (1989a) and Jatenco-Pereira, Opher, & Yamamoto (1994) in the solar wind, Jatenco-Pereira & Opher (1989b) in protostellar winds, Jatenco-Pereira & Opher (1989c) in late-type giant stars, dos Santos, Jatenco-Pereira, & Opher (1993a, 1993b) in Wolf-Rayet stars, Gonçalves, Jatenco-Pereira, & Opher (1993a, 1996) in quasar clouds, and Gonçalves, Jatenco-Pereira, & Opher (1993b) in extragalactic jets.

This article proposes the damping of global Alfvén waves (GAWs) as a new mechanism for heating the magnetosphere of young stars. Shear, kinetic (or drift kinetic) and global Alfvén waves are different types of Alfvén waves. Each of them has its own particular characteristics. The GAW is an eigenmode of a specific kind of Alfvén wave that is found in bounded current-carrying plasmas (Ross, Chen, & Mahajan 1982). Classical Alfvén waves (CAWs) exist in homogeneous plasmas, and they are weakly dissipated. CAWs have no perpendicular dispersion: $\omega = k_{\|} c_{\mathrm{A}}$, where ω is the wave angular frequency, $c_{\mathrm{A}} = B/(4\pi\rho)^{1/2}$ is the Alfvén velocity, B is the ambient magnetic field, ρ is the plasma density, and $k_{\|}$ is the projection of the wave vector on the magnetic field direction. When there is a density gradient perpendicular to the magnetic field lines, a local Alfvén wave resonance or shear Alfvén wave (SHAW), which strongly dissipates as a result of phase mixing, can be excited (Hasegawa & Uberoi 1982). Due to the finite ion Larmor radius and the thermal motion of the electrons along the magnetic field, CAWs and SHAWs can be transformed into kinetic Alfvén waves (KAWs) (or drift-kinetic waves) (Hasegawa & Uberoi 1982), which have $k_{\perp}$ on the order of the inverse of the ion Larmor radius. KAWs dissipate strongly by electron Landau or collisional damping. GAWs, the particular type of Alfvén wave discussed in this article, occur in current-carrying filaments and are created by the Hall effect and/or by the curvature of the magnetic field lines produced by the parallel current. They have $k_{\perp}$ on the order of the inverse of the filament radius. Because of their specific dispersion, the difference between the oscillations of electrons and ions in GAWs is very small. As a result, the collisional and Landau dissipation of these waves is very weak. It should be noted that, while SHAWs and KAWs are strongly damped and deposit their energy rapidly, GAWs are weakly damped and, therefore, deposit their energy over long distances.

The GAWs has not been previously analyzed as a possible mechanism for the energy transport to the magnetosphere of T Tauri stars. They were predicted in numerical calculations (Ross et al. 1982) using a cylindrical model for magnetized plasmas with an axial current and were observed later in tokamak experiments. GAWs are excited in plasmas in a helical magnetic field, with the poloidal component produced by an axial current, $B_\theta \approx 2\pi a B_z/L$, where B_z is the axial magnetic field component and a and L are the plasma radius and length, respectively. The so-called tokamak safety factor, $q = rB_z/RB_\theta$, is considered to be unity. GAWs can exist in linear structures as well as in toroidal structures, such as tokamaks. Besides tokamak experiments, a few experiments have been made in long linear machines with an axial current. In one such experiment, Tang & Luhmann (1976) showed that a strong axial current can not only allow GAWs to propagate, but can also destabilize them in the drift frequency band. Spontaneously excited GAWs were also observed by Amagishi et al (2002) during axial injection of plasma into a linear machine.

In cold plasmas with temperatures less than $\sim$0.5 eV, GAWs dissipate via electron-ion collisions. However, in hot plasmas, when the Alfvén velocity, $c_{\mathrm{A}} = B/(4\pi m_i n_e)^{1/2}$, is of the order of the electron thermal velocity, $v_{Te} = (T_e/m_e)^{1/2}$, GAWs dissipate via electron Landau damping. The electron Landau damping mechanism is very effective when waves interact with a group of electrons that have velocities approximately equal to the wave phase velocity, $\omega/k_{\|} = c_{\mathrm{A}}$, where ω is the frequency and $k_{\|}$ is the wavenumber parallel to the magnetic field lines. Electromagnetic field components related to GAWs are proportional to $\exp[i(m\theta + k_z z - \omega t)]$, with poloidal m and axial k_z wavenumbers. The requirement for these waves to propagate is that $m = -1$ and $k_z < 0$, in the case of current flowing along the magnetic field. A GAW has a very large quality factor, ratio of frequency to dissipation decrement, $Q = \omega/\gamma \gg 1$ and a very long dissipation length in comparison to their wavelength, $L_{\mathrm{A}} \gg 1/k_{\|}$. Thus, it is a very good candidate to explain plasma heating far from a source, such as in solar loops (Hollweg 1990; Elfimov et al. 1996). In addition, a GAW is able to drive the current, which can be calculated by balancing the wave momentum transfer force with the electron-ion friction force (Elfimov et al. 1996).

Here we have developed a new model, based upon well-known plasma physics effects, of the energy deposition by GAWs that propagate along filaments, similar to plasma waveguides. We show that a filament current may be induced by a strong $\boldsymbol{v} \times \boldsymbol{B}$ electric field in the accretion region or by shock waves. The process of plasma penetration across perpendicular magnetic field lines in the accretion region is accompanied by strong oscillations of magnetic field lines. The part of the oscillation spectrum, excited as GAW eigenmodes, is selected by the filaments and transferred along the magnetic field lines with plasma heating occurring far from the accretion region. The GAW eigenmodes deposit their energy into the filaments, raising the temperature of the magnetosphere.

GAWs can be produced in the ionization shock layer, Δ (Liberman & Velikovich 1986), which is formed at the radius at which the disk is disrupted by the magnetic field of the star. A fully ionized plasma is produced in the ionization shock layer if the kinetic energy of the accreting particles is substantially larger than that of the ionization potential. In the quasi-equilibrium case for the layer, radial flux momentum is balanced by an equatorial ring current with a current density j_ϕ that is perpendicular to the magnetic field, $\rho V_r^2/2\Delta = j_\phi B$, where ρ is density of the accreting particles, V_r, the radial velocity of the particles, and j_ϕ is the density of the drift current. It is well known that the drift current perpendicular to a magnetic field is the source of drift instabilities, including long-wavelength Alfvén waves (Mikhailovskii 1992). These waves can easily convert into GAWs when they are leaving the unstable truncated region.

Magnetosonic shock waves can also produce GAWs. In the process of plasma penetration across the perpendicular magnetic field lines in the accretion region, oblique magnetosonic shock waves can be excited (Liberman & Velikovich 1986) creating strong oscillations of the magnetic field lines. The dissipation length of magnetosonic shock waves is very short, on the order of the magnetosonic wavelength. Plasma compressed by the magnetosonic shock is injected along the magnetic field out of the truncated region, which can immediately excite GAWs, as was demonstrated in experiments by Amagishi et al. (2002) in a linear machine with axial plasma injection. Excited shock waves propagating across the dissipation layer can also directly produce perpendicular magnetic field oscillations, which can induce an electric field with an amplitude on the order of $\boldsymbol{v} \times \boldsymbol{B}/c$. This electric field can produce the initial parallel current, needed to form the filaments. The electron current is expected to be maintained in the filament due to the ponderomotive force of the GAWs (Elfimov et al. 1996). Part of the oscillation spectrum induced by the oblique magnetosonic shock waves is directly selected by the filaments as GAW eigenmodes, which can travel along the magnetic field lines.

2. MAGNETOSPHERE ACCRETION MODEL

We study here a two-fluid magnetohydrodynamic model of a young star, accreting plasma (see Fig. 1). The standard parameters of CTTSs, similar to those used by Vasconcelos et al. (2002), are assumed: star radius $R_* = 10^{11}$ cm, truncated radius $R_{\rm tr} = 2 \times 10^{11}$ cm, truncated depth $\Delta_{\rm tr} \approx 3 \times 10^{10}$ cm, magnetic field at the star's surface $B_{\rm st} = 1$ kG and $B_{\rm tr} \approx 0.1$ kG in the truncated region, where the electron density is $\bar{n}_{\rm tr} = 3.0 \times 10^{11}$ cm^{-3}. The length $L_{\rm mf}$ of the magnetic field lines from the shock at the star's surface to the truncated region is $\approx 1.2R_*$. The velocity of the shock is $v_{\rm sh} \approx 2.5 \times 10^7$ cm s^{-1} at the star's surface and $v_{\rm tr} \approx 3.5 \times 10^7$ cm s^{-1} in the truncated region. The ionization rate parameter $\langle\sigma v\rangle_{\rm ion}$ for $T_e = 1.5$ eV is $\sim 3 \times 10^{-13}$ cm^3 s^{-1} (Delcroix 1965). The accretion energy density is defined by the ratio of the energy flux density to the path length $L_{\rm mf}$. Balancing 90% of the accretion power density $m_i n_0 v_{\rm tr}^3/L_{\rm mf}$ with the ionization power density $\langle\sigma v\rangle_{\rm ion} n_e n_0 E_{\rm ion}$, we obtain a plasma with an average density along the magnetic field of $\tilde{n} \approx 3.3 \times 10^{11}$ cm^{-3}.

We assume that the magnetic field connecting the truncated disk and the star's surface consists of filaments, along which the GAW propagates. The filament current can be driven by the wave ponderomotive force (see discussion below) and/or by a magnetodynamo in the truncated region of the disk. The current, $I = 5aB_{\theta,ef}$, and current density, $j = I/\pi a^2 \approx 16$ statA cm^2, in a filament of radius a can be produced by the electric field, $j/\sigma \approx 10^{-12}$ statV cm^{-1}, that is sufficient to create the required poloidal magnetic field B_θ for the GAW excitation. This electric field can be generated by the induction of a perpendicular electric field, $E_\perp = B_{\rm tr} v_{\rm tr}/c \approx 0.05$ statV cm^{-1}, in the truncated region of the disk due to the magnetodynamo $\boldsymbol{v} \times \boldsymbol{B}$ effect (see Fig. 1). A difference of potential on the scale of the filament radius is of the order of 2.5×10^3 statV. This potential is much higher than is necessary and can generate a filament current with a hot electron tail and a characteristic velocity higher than that of the Alfvén velocity $c_{\rm A}$, as was found in the plasma focus device. We expect that the electrons in the tail will remain hot in the filament by their interaction with the GAWs (Elfimov et al. 1996).

For the parameters of the star assumed above, the phase velocity of a GAW, $c_{\rm A}(R_{\rm tr})$, is $\sim 3 \times 10^8$ cm s^{-1} at the center of the filament. Taking into account the plasma resistance (see, e.g., Ginsburg 1961), the dissipation length of the Alfvén waves can be estimated to be

$$L_{\rm A} \approx 8\pi \frac{\sigma c_{\rm A}}{k_\parallel^2 c^2} \approx 1.2 \times 10^{11} \text{ cm}, \qquad (1)$$

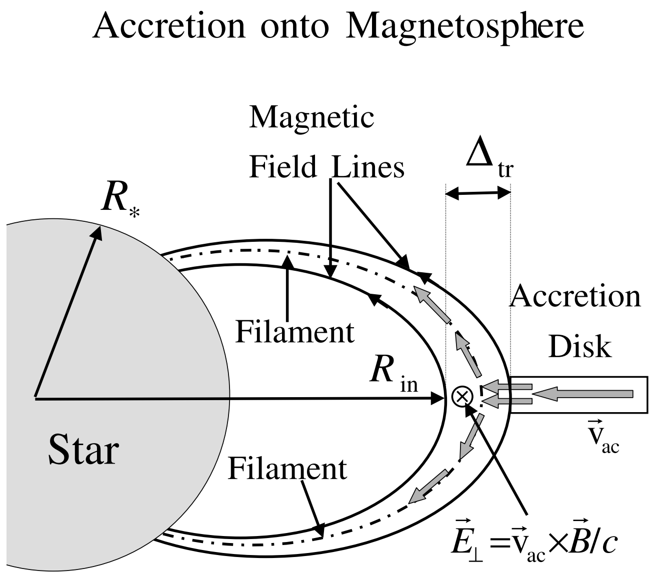

Fig. 1.—Sketch of a young accreting star of radius R_* and truncation depth $\Delta_{\rm tr}$. The electric field, designated by $\oplus$, is generated by the $\boldsymbol{v} \times \boldsymbol{B}$ effect due to the interaction of the magnetic field lines from the star with the accreting plasma in the truncated region of the disk.

where

$$\sigma = \frac{\omega_{pe}^2}{4\pi\nu_{\rm ei}} \approx 1.6 \times 10^{13}\ T_e^{3/2} \text{ s}^{-1}, \quad k_\parallel = 3 \times 10^{-5} \text{ cm}^{-1}.$$

This $k_\parallel$ is a maximum value, determined by the condition that the dissipation length be sufficient so as to explain the plasma heating along the magnetic field from the truncated region to the star's surface.

Assuming a conversion of 5% of the total accreting plasma energy flux, $S = (1/2)n_n m_i(v_{\rm sh}^3 + v_{\rm tr}^3)$, into the Alfvén wave flux, $S_{\rm A} = P_{\rm A} L_{\rm A}$, we obtain a wave dissipation rate of $P_{\rm A} = 0.0039$ erg cm^{-3} s^{-1}. This dissipation rate produces a wave momentum transfer force $P_{\rm A}k_\parallel/\omega$ (see Elfimov et al. 1996). Balancing the wave momentum transfer force with the electron-ion friction force $\nu_{\rm ei} m_e n_e V_e$, we obtain the density of the driven current,

$$\langle j_{\rm cd}\rangle = -\frac{|e|k_\parallel P_{\rm A}}{m_e \nu_{\rm ei,ef}\,\omega}. \qquad (2)$$

Using a reduced friction, $\nu_{\rm ei,ef} \approx \nu_{\rm ei}(v_{Te}/c_{\rm A})^{3/2}$, for the electron tail with effective velocity $\approx c_{\rm A}$ and $\omega = k_\parallel c_{\rm A} = 9 \times 10^3$ s^{-1} ($c_{\rm A} = 3. \times 10^8$ cm s^{-1}), we obtain the required current density, $\langle j_{\rm cd}\rangle \approx 16$ statA cm^{-2}, in the filament. In this case, the electron tail that transports the current along the filament can be supported by the GAW via the electron Landau damping, while the current in the filament can be driven by the GAW.

Here we also present the results of calculations for the GAW in the filament. In order to calculate the wave field and dissipation, we use the eikonal model to analyze the wave propagation along the filament, $\exp[i(m\theta + \int k_z\,dz - \omega t)]$, where z is the coordinate along the filament axis and θ is the poloidal angle. In this case, in order to simplify the GAW calculations using numerical codes (Amarante-Segundo et al. 1999; Galkin et al. 2002), instead of a dipole magnetic field, we assume a cylindrical model for the filament plasma with the current flowing along a magnetic field that has a helical magnetic field line configuration. To calculate the wave characteristics along the filament, we take the major radius $R_0 = 10^{11}$ cm comparable to the star's radius and the minor radius $a = 5 \times 10^5$ cm. The calculations are carried out with the electron density profile of the form $n_e = n_0(1 - r^2/a^2) + n_a$, with $n_0 = 5 \times 10^{11}$ cm^{-3} and $n_a = 5 \times 10^{10}$ cm^{-3}. The temperatures are taken as $T_{e0} = 1.6$ eV and $T_{i0} = 0.5$ eV. The ion density is chosen so as to satisfy the requirement of charge neutrality, $Zn_Z + n_i = n_e$, where n_i and n_Z are the densities of hydrogen and the other ions, respectively. In accordance with the Spitzer conductivity $\propto T_e^{3/2}$, the current density profile has the form $j = j_0(1 - r^2/a^2)^3$. The value of the safety factor, $q = rB_z/RB_\theta$, is assumed to be unity at the filament axis and to monotonically increase up to four at the plasma boundary. In Figure 2, we show the characteristic profile of the magnetic field as well as the dissipated power of the GAW for the filament parameters discussed above.

In Figure 2, we observe the peaking of the dissipation at the filament center, which predicts filament center peaking of the electron temperature distribution, as well. The GAW heats the core of the filament to higher temperature, while reducing the plasma temperature at the filament border due to heat diffusion. The axial wavenumber of the GAW, $k_z = \omega/c_A$, varies slowly along the magnetic field lines since it depends on changes in the local magnetic field and density.

3. CONCLUSIONS

Our analysis of GAWs in the magnetospheres of CTTSs shows that (1) the energy of the shock (and/or accretion disk region) can be transported from the surface of the star (and/or accretion disk region) to the magnetosphere region by GAWs via current-carrying filaments; (2) the dissipation length of GAWs is on the order of the truncation radius; (3) the conversion of only a few percent of the shock energy into GAWs is required in order to heat the filaments up to the observed temperature of the star's magnetosphere; (4) the The current in the filament may be induced by the electric field, created by the $\boldsymbol{v} \times \boldsymbol{B}$ magnetodynamo effect in the truncated region of the disk. However, the major part of the current in the filaments is driven by GAWs.

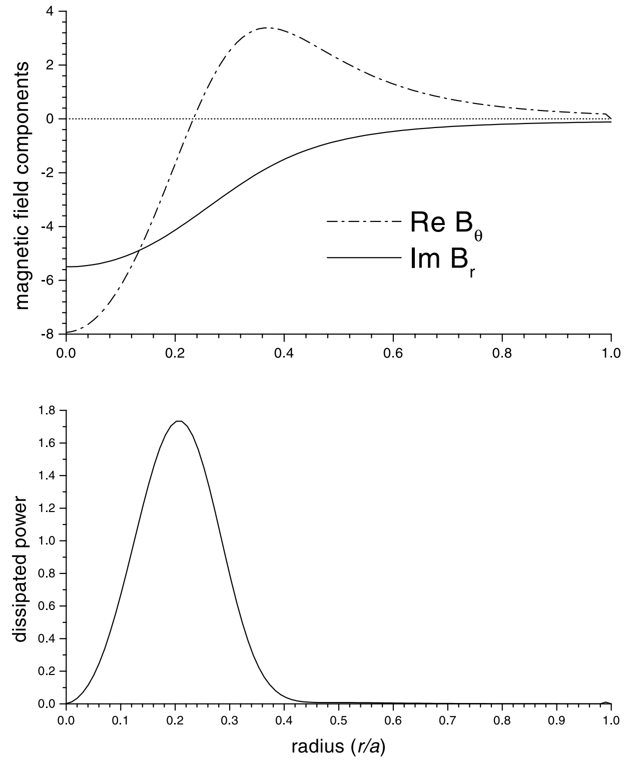

FIG. 2.—Plot of $B_{r,\theta}$-components of the GAW field and dissipated power across the filament cross section for a frequency of 1.4 kHz and the parameters $B = 1$ kG, $q_0 = 1.0$, $n_0 = 5 \times 10^{11}$cm^{-3}, $T_{e0} = 1.6$ eV, and $T_{i0} = 0.5$ eV.

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