Rayleigh-Taylor-Unstable Accretion and Variability of Magnetized Stars: Global Three-Dimensional Simulations

Akshay K. Kulkarni, Marina M. Romanova

Dept. of Astronomy, Cornell University, Ithaca, NY 14853

akshay@astro.cornell.edu, romanova@astro.cornell.edu

ABSTRACT

We present results of 3D simulations of MHD instabilities at the accretion disk-magnetosphere boundary. The instability is Rayleigh-Taylor, and develops for a fairly broad range of accretion rates and stellar rotation rates and magnetic fields. It produces tall, thin tongues of plasma that penetrate the magnetosphere in the equatorial plane. The shape and number of the tongues changes with time on the inner-disk dynamical timescale. In contrast with funnel flows, which deposit matter mainly in the polar region, the tongues deposit matter much closer to the stellar equator. The instability appears for relatively small misalignment angles, $\Theta \lesssim 30^\circ$, between the star’s rotation and magnetic axes, and is associated with higher accretion rates. The hot spots and light curves during accretion through instability are generally much more chaotic than during stable accretion. The unstable state of accretion has possible implications for quasi-periodic oscillations and intermittent pulsations from accreting systems.

Subject headings: accretion, accretion discs; instabilities; MHD; stars: oscillations; stars: magnetic fields

1. Introduction

The geometry of the accretion flow around magnetized stars is an important factor in determining the observed spectral and variability properties of the accreting system. An accretion disk around a magnetized central object is truncated at the distance from the central star where the magnetic energy density becomes comparable to the matter energy density. Beyond that point, the gas can accrete to the star (1) through funnel streams, or magnetospheric accretion (e.g., Ghosh and Lamb 1979), or (2) through plasma instabilities at the disk-magnetosphere interface (e.g., Arons and Lea 1976; Elsner and Lamb 1977). The geometry of the matter flow in these two regimes is expected to be very different. In general, the Rayleigh-Taylor (RT), or interchange, instability is expected to develop at the disk-magnetosphere interface because of the high-density disk matter being supported against gravity by the low-density magnetospheric plasma. The Kelvin-Helmholtz (KH) instability is also expected to develop because of the discontinuity in the angular velocity of
matter at the boundary. The inner disk matter is expected to rotate at the local Keplerian velocity, while the magnetospheric plasma corotates with the star.

Two- and three-dimensional simulations have shown accretion through funnel streams (Romanova et al. 2004; Kulkarni and Romanova 2005). Here we report on accretion through the Rayleigh-Taylor, or interchange, instability in global 3D MHD simulations.

2. Simulation Results

Our numerical model and reference values are described in Kulkarni and Romanova (2008). We chose the following parameters for our main case: dipole moment $\mu = 2$, corresponding to an equatorial surface magnetic field of $B = 2$, misalignment angle $\Theta = 5^\circ$, viscosity parameter $\alpha = 0.1$, stellar rotation period $P = 3$, initial disk radius $= 2$. The corotation radius, which is the radius at which the orbital rotation rate of the disk matter equals the star’s rotation rate, is $r_{\text{cor}} = 2$.

Fig. 1.— Accretion through funnels (a) and instability (b). A constant density surface is shown. The lines are magnetospheric field lines. The translucent disc denotes the equatorial plane. The star’s rotation axis is in the z-direction. (c) A tongue of gas, shown by density contours in the equatorial plane, pushing aside magnetic field lines on its way to the star.

Figure 1 compares the accretion flow in the stable and unstable cases. Unstable perturbations at the disk-magnetosphere boundary grow and disk matter penetrates the magnetosphere in the form of tongues of gas travelling through the equatorial plane by prying the field lines aside. Matter energy density dominates inside the tongues. When they come closer to the star, they encounter a stronger magnetic field, which stops their equatorial motion. At this point the tongues turn into miniature funnel-like flows following the field lines. They deposit matter much closer to the star’s equator than true funnel flows do.

Figure 2 shows equatorial slices of the circumstellar region at various times. The density enhancements which result in the formation of the tongues can be seen at the bases of the tongues. The number of tongues changes with time of its own accord, without any artificially introduced perturbation. The total number of tongues at any given time is of the order of a few.
3. Effect of the Instability on Hotspots and Variability

Figure 3 compares the hot spots on the star’s surface in the stable and unstable cases. We see that the spots are very different in the two cases. Each tongue creates its own hot spots when it reaches the star’s surface. Therefore, the shape, intensity, number and position of the spots change on the inner-disk dynamical timescale.

We calculate lightcurves from the hotspots for various viewing directions, taking into account the general relativistic effects of light bending and gravitational redshift, and the Doppler effect (Poutanen and Gierliński 2003, Kulkarni and Romanova 2005). The lightcurves show oscillations superimposed on a slowly varying background, which we subtract out. Figure 3a shows the lightcurve and its fourier and wavelet spectra for one of our stable accretion cases. We see a definite peak at the star’s frequency. As the wavelet spectrum shows, there is no drift in the frequency. When the accretion is unstable, the tongues and the hotspots they produce rotate around the star’s
axis at a frequency different from the star’s rotation frequency. Therefore, the star’s frequency can disappear completely from the power spectrum, as seen for the visibly chaotic matter lightcurve in Figure 3b. A multitude of other peaks appears in the power spectrum instead. In this case, there are two prominent peaks with $\nu/\nu_* = 1.2$ and 1.8. There is also considerable drift in the frequency, as seen from the wavelet spectrum.

4. Empirical conditions for the existence of the instability

To investigate the parameter ranges over which the instability appears, we performed simulation runs for a variety of values of the accretion rate and and the star's rotation period $P$, for two magnetospheric sizes $r_m/R_* = 2-3$ and 4-5, at misalignment angle $\Theta = 5^\circ$. The accretion is unstable if

$$M \geq M_{\text{crit}} \approx x M_\odot \text{ yr}^{-1} \left( \frac{B_{10^9} \text{ G}}{10^9} \right)^2 \left( \frac{R_{10 \text{ km}}}{10 \text{ km}} \right)^{5/2} \left( \frac{M_{1.4M_\odot}}{M_\odot} \right)^{-1/2},$$

where $x = 1.8 \times 10^{-8}$ and $2.2 \times 10^{-9}$ for the small and large magnetospheres.

5. Discussion

Accretion through instability is expected to occur in most accreting systems for typical values of mass, radius, surface magnetic fields and accretion rates. One of the most interesting observational consequences of accretion through instabilities is the effect on the variability. Light curves associated with funnel accretion show clear pulsations at either the star’s frequency or twice that, depending on the misalignment angle and the viewing geometry. In contrast, lightcurves associated with unstable accretion do not show very clear signs of periodicity. Since unstable accretion occurs at high accretion rates, this has a few implications: (1) If the accretion rate is close to the boundary between stable and unstable regimes, then slight changes in the accretion rate can cause the accretion to episodically switch between stable and unstable, causing corresponding appearance and disappearance of pulsations. This might be a possible explanation for the behaviour of intermittent pulsars (Altamirano et al. 2008; Casella et al. 2008). One of the attractive features of this idea comes from the fact that during stable accretion, the azimuthal location of funnels with respect to the star is fixed, even across periods of unstable accretion. The pulsations in intermittent pulsars would therefore be expected to be coherent in phase across periods of lack of pulsations. This “phase memory” has been observed in the intermittent pulsars mentioned above. (2) The stellar magnetic field is not buried even in the unstable cases that we have considered. So pulsations may be undetectable at even lower accretion rates than those required for field burial. (3) The fourier spectra of the unstable lightcurves do show some peaks. These appear because the number of tongues does not usually change very rapidly. If a certain number of tongues dominates for a
significantly long time, it may lead to quasi-periodic oscillations in the lightcurves (Li and Narayan 2004), which may be important for understanding Type II (accretion-driven) bursts in LMXBs.

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