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DISK INSTABILITIES AND QUASI-PERIODIC OSCILLATIONS

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RESUMEN

Presento un reporte de los avances realizados en los ultimos años en la explicación de las oscilaciones cuasi-periódicas de baja frecuencia en microcuasares a través de la inestabilidad de acreción-eyección. Discuto también la posibilidad de que este modelo pueda dar cuenta de la variabilidad a largo plazo en estas fuentes. A continuación considero una segunda inestabilidad, relacionada con la primera y al mismo tiempo con modelos de disco-sismología de discos, y muestro como puede aplicarse al estudio de las oscilaciones cuasi-periódicas de alta frecuencia en microcuasares, así como a las ráfagas en Sgr A*, el agujero negro masivo en el centro de la Vía Láctea.

ABSTRACT

In this paper I review progress made in the last few years in explaining the low-frequency QPO of microquasars by the Accretion-Ejection Instability, and how this may guide us in understanding the short and long term variability of these sources. I then turn to another, closely related instability, which also relates to diskoseismologic models. I show how it might apply to explain the high-frequency QPO of microquasars, and the flares in Sgr A*, the massive black hole at the Galactic Center.

Key Words: **ACCRETION, ACCRETION DISKS — GALAXY: CENTER — INSTABILITIES — MAGNETOHYDRODYNAMICS — PLASMAS**

1. INTRODUCTION

The Quasi-Periodic Oscillations (QPO) of X-ray binaries present decisive challenges to our understanding of accretion processes in these sources. The low-frequency one, common to neutron-star and black-hole binaries, is so strong that it must represent a major phenomenon for accretion and jet formation in the inner region of the disk. The high-frequency ones differ between the two classes, but are commonly believed to trace phenomena at the inner edge of the disk, *i.e.* the disk/magnetosphere interface in neutron stars, and the marginally stable orbit (MSO) in black hole disks.

Although it is now clear that the Magneto-Rotational Instability (MRI: Balbus & Hawley 1991) is a convincing explanation for turbulent accretion in magnetized disks, it has not thus far allowed to produce quasi-periodic activity; on the other hand we have in recent years developed the theory and numerical simulation of another mechanism, the Accretion-Ejection Instability; for reasons that will be explained below it can exist only in the inner region of the disk, and can thus not explain accretion over the whole disk. But it presents characteristics which make it well adapted to explain the low-frequency QPO observed a a frequency of ~ 1 to a few tens of Hz in X-ray binaries.

In this paper I will review the theory of the AEI, the reasons which make us consider it as a very interesting candidate to explain the LFQPO, and the model we have elaborated from there to try and understand the cycles of the microquasar GRS 1915+105 — and maybe, beyond that, the longer term variability of this source. I will then present preliminary results concerning another instability, the Rossby-Wave Instability (RWI: Lovelace et al. 1999). It is closely related to the AEI, but I will also show that, near the MSO, it can be considered as the g-mode of diskoseismologic models (Nowak & Wagoner 1991). I will discuss its potential to explain the high-frequency QPO, and conclude by showing how it might explain the flares of the black hole in Sgr A*, the black hole at the Galactic Center. I will first of all start by discussing the magnetic configuration of magnetized accretion disks, which conditions all these results.

2. THE MAGNETIC CONFIGURATION

In order to discuss instabilities one has to start from a definite equilibrium configuration, and we hit here our first difficulty with MHD: such equilibria are hard to come with for magnetized disks, because

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MHD imposes quite restrictive constraints, *e.g.* that a field line has to rotate solidly at a given rotation frequency: this can lead to a gross imbalance between the gravitational force from the central object and the centrifugal force, giving a strong acceleration along the field lines, whence the family of MHD jet models which started with Henriksen & Rayburn (1971) and Blandford & Payne (1982). But these models, if one seeks a complete solution including the disk and the jet, require assumptions on an anomalous dissipation in the disk (Casse & Ferreira 2000). Furthermore, the description of instabilities of equilibria including such flows (in addition to differential rotation in the disk) becomes rapidly intractable, so that analytical work has been mostly restricted to configurations with either a purely azimuthal or a purely vertical magnetic field.

A disk threaded by a vertical magnetic field is indeed the configuration favored by jet models, where the gas flows along field lines to form the jet. The net flux threading the disk can have been advected with the gas which formed the disk, or result from a dynamo action in the disk (provided a reverse flux is allowed in the outer parts of the disk). On the other hand, most numerical simulations of turbulence in magnetized disks have focused for simplicity on models with no net vertical flux, and with a relatively low magnetization, because these are sufficient conditions to produce the Magneto-Rotational Instability. It has been argued (Lubow, Papaloizou, & Pringle 1994) that turbulent magnetic diffusivity would prevent vertical magnetic flux to penetrate in the disk. However that result rests on a number of assumptions on the diffusivity, and on the boundary conditions on the gas feeding the disk from outside. Furthermore, axisymmetric numerical simulations (Casse & Keppens 2002) performed in conditions which should favor this result (strong magnetic diffusivity, no viscosity) do show magnetic flux dragged in by the gas flow.

Jet models also converge to require that the magnetic pressure be of the order of equipartition with the gas pressure ($\beta \equiv 8\pi p/B^2 \sim 1$), in order to allow a redirection in the vertical direction, along the field lines, of the accretion energy and angular momentum extracted by the turbulent viscosity and magnetic diffusivity in the disk. Global MHD simulations, on the other hand, have mostly been conducted with much weaker magnetic field, $\beta \gg 1$. One thus has a dichotomy of models, ones with a weak and mostly toroidal field, and ones with a stronger and mostly poloidal one. But the former, more easily amenable to extensive numerical simulations, have failed to show either jets or Quasi-Periodic Oscillations (QPO), even in recent models incorporating the full set of general relativistic equations.

The Accretion-Ejection Instability (AEI, Tagger & Pellat 1999), to which most of this paper is dedicated, has been studied with this in mind. It can exist only in the inner region of the disk, and thus cannot claim to explain accretion elsewhere. On the other hand it exists precisely in the conditions required by jet models (poloidal field, $\beta \sim 1$), it does produce behaviors which compare favorably with the low-frequency QPO, and it has the ability to transfer vertically along the field lines a significant part of the accretion energy and momentum extracted from the disk, offering the prospect to directly feed the jet or wind from the disk turbulence. Furthermore, we have in recent years built up a more global scenario for the spectacular variability of the microquasar GRS 1915+105; this "Magnetic Floods" scenario, which will be presented below, is based on a systematic comparison of the properties of the instability with the observed behavior of the source.

I will end this paper by presenting briefly recent results obtained on the Rossby-Wave Instability (RWI). This instability is closely related to the AEI, but occurs in different conditions. We have used it recently to explain the flares of the black hole at the Galactic Center (Tagger & Melia 2006), and also to address the difficulties due to the presence of a "Dead Zone" in protostellar disks (Varnière & Tagger 2006). Its properties might be used to explain the high-frequency QPOs of microquasar, in particular their 3:2 frequency ratio.

3. ACCRETION-EJECTION INSTABILITY AND LOW-FREQUENCY QPO

3.1. *Accretion-Ejection Instability*

The AEI is fundamentally an instability of the disk and its corona. However a fully consistent, 3D model is beyond the possibility of analytical theory. Since the instability exists already in an infinitely thin disk in vacuum, it was first studied in that configuration (Tagger & Pellat 1999), and the theory was later extended perturbatively to include the 3D effect of the corona (Varnière & Tagger 2002). In the same manner, as 3D MHD simulations are not yet possible in this configuration, only simulations of a thin disk in vacuum have been performed (Caunt & Tagger 2001), confirming the analytical theory and providing a first view at the non-linear evolution of the instability.

As explained in the introduction, the AEI occurs in a disk threaded by a vertical magnetic field of the

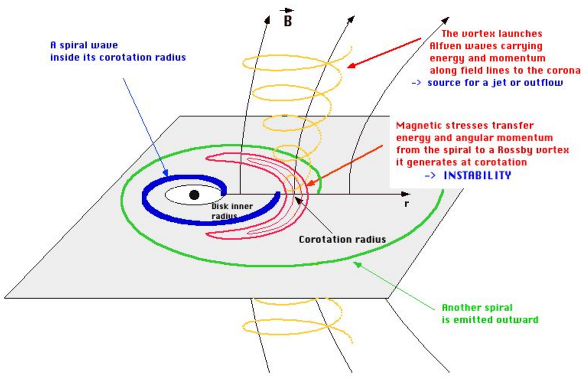

Fig. 1. The AEI is a standing pattern formed of spiral density waves made unstable by coupling with a Rossby wave they generate at the radius where they corotate with the gas. The Rossby wave, twisting the footpoints of magnetic field lines threading the disk, in turn emits the accretion energy as Alfvén waves in the corona.

order of equipartition with the gas pressure. It is unstable if the radial gradient of a certain quantity $\mathcal{L}_B = \kappa^2\Sigma/2\Omega B$ is positive (here Ω and $\kappa =' \Omega^2 + 2\Omega\Omega' r$ are the rotation and epicyclic frequencies, and Σ is the surface density in the disk); this condition is fulfilled, in particular, in self-similar jet models. Figure 1 shows a schematic description of the AEI, which is formed of:

- a spiral density wave in the inner region of the disk; this wave, traveling inward, is reflected at the inner disk edge into an outgoing one; the latter is reflected inward at the radius where it corotates with the gas. This forms a cavity where the wave is trapped, selecting by an integral phase condition (*i.e.* that the wave returns after one cycle with the same phase) a discrete set of possible frequencies ("normal modes"), of which only the fundamental matters here: its frequency is typically $\sim$ .1 − .3 times the rotation frequency at the inner disk edge.
- and a Rossby wave generated by the spiral wave at its corotation radius.
- another spiral wave, of lesser importance, is emitted outward beyond corotation.

The waves form a standing pattern which grows exponentially as they exchange energy and angular momentum: technically, the spiral wave has a negative energy (*i.e.* it decreases the total energy of the system), while the Rossby wave has positive energy, so that growth results from both waves gaining in amplitude while the total energy remains constant. This coupling between the spiral and Rossby waves is known as the corotation resonance.

The same features are involved in the self-gravity-driven spiral instability of galaxies, or in the Papaloizou-Pringle instability (PPI, Papaloizou & Pringle 1985) of unmagnetized disks. The main difference is that in those cases amplification results mostly from the coupling with the outgoing spirals, and that in the PPI case the amplification is weak and applies only to small azimuthal wavelength modes. In both cases the corotation resonance is usually stabilizing (with reasonable radial density profiles), as the critical quantity is $\mathcal{L} \equiv \kappa^2/(2\Omega\Sigma)$. In a magnetized disk the amplification by coupling to the outgoing spiral is also weak but applies to larger scale modes (Tagger et al. 1990), essentially $m = 1$ (a one-armed spiral structure) for the AEI.

The main difference in a disk threaded by a poloidal magnetic field is twofold: first, the corotation resonance is found to be most often destabilizing (*i.e.* the radial gradient of $\mathcal{L}_{\mathcal{B}}$ is positive) and to give a significant growth rate; and second, it changes nature when the corona is included: without a corona the accretion energy extracted from the disk by the spiral is stored in the Rossby vortex, and this has led Narayan, Goldreich, & Goodman (1987) to speculate that the corotation resonance might saturate, in the same manner as Landau damping does in a plasma (the analogy with Landau damping is actually much deeper, but this will be discussed elsewhere). Here on the other hand the twisting motion applied by the Rossby vortex to the footpoints of the field lines threading the disk gets propagated along the field lines as Alfvén waves. A detailed calculation (Varnière & Tagger 2002) shows that this mechanism can be efficient enough to redirect toward the corona a significant fraction of the accretion energy extracted from the disk by the spiral wave. This fraction could be directly compared with the empirical factor $f \equiv$ (energy transferred to the corona/energy extracted from the disk) used in models of disks in their low/hard state (Merloni & Fabian 2002).

3.2. *AEI and LFQPO*

We have presented a number of arguments supporting the AEI as the source of the low-frequency QPO (LFQPO):

- its frequency is in agreement with the correlation found by Psaltis, Belloni, & van der Klis (1999), placing the QPO frequency at $\sim$ .1 times the rotation frequency at the inner disk edge.

- A detailed discussion of observational results (Sobczak et al. 2000), noting the difference between the QPO behaviour in GRO J1655-40 and in other sources, allowed us to explain it by changes in the QPO properties, when the inner disk edge approaches the Marginally Stable Orbit (MSO). This is due to relativistic effects, changing the rotation curve near the MSO (Varnière, Rodriguez, & Tagger 2002a; Rodriguez et al 2002).

- contrary to other proposed mechanisms, the AEI does not need an external excitation source, since it is an instability and can thus spontaneously reach very high amplitudes. This is a real challenge for models, given the very high amplitude (up to 40% rms) sometimes reached by the QPO. Numerical simulations (Caunt & Tagger 2001) have confirmed that the AEI does reach a high amplitude, although the realistic connection between this and the modulation of the disk and coronal emission remains to be done.

- The physics of the AEI implies that accretion energy is extracted from the disk but, rather than heating it locally by a viscous process, is transported away by waves. As mentioned above, a part of this energy ends up in the corona. This (cold disk and energized corona) is consistent with the fact that the LFQPO is observed in the low-hard state, where the disk emission is weak and the coronal one strong - to the point that the LFQPO is sometimes considered as a an intrinsic propery of that state (McClintock & Remillard 2006).

- A last observation may be crucial in this view: we have found at least one case (Rodriguez et al. 2002) that the LFQPO occurs just *before* the transition from the high/soft to the low/hard state, in GRS 1915+105. If confirmed, this would prove that the QPO may be the *cause*, and not the *consequence* of this transition: *i.e.* that it is the formation of the QPO which cools down the disk and energizes the corona.

3.3. *Magnetic floods*

From this we have elaborated a model, called "Magnetic Floods", to try and understand the cycles of GRS 1915+105, in particular the β class of Belloni et al. (2000). This is a cycle of oscillations, lasting typically 30 minutes, and during which the source alternates between a high/soft and a low/hard

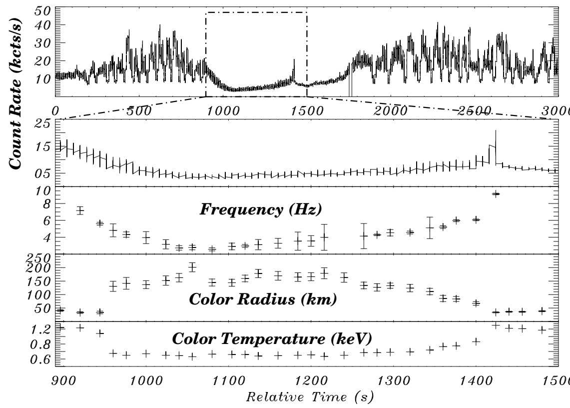

Fig. 2. A typical cycle (β class of Belloni et al. 2000) of GRS 1915+105 showing the X-ray light curve, the QPO frequency when it is detected, and the color radius and disk temperature extracted from spectral fits (Rodriguez et al. 2002).

state. The latter ends with a "spike", associated with IR and radio observations of a blob ejected at relativistic speeds (see e.g. Rothstein, Eikenberry, & Matthews 2005). It is during that state that the LFQPO is seen, at a smoothly varying frequency.

The model (Tagger et al. 2004) was built by starting from the assumption that the AEI does cause the QPO, and by comparing the properties of the instability with what we know of the source and its behavior. The resulting scenario is quite consistent, and leads us to suggest that the variability of the source (both during the cycles and on a longer time scale) is governed by the relative evolution of the magnetic flux in the disk and the flux trapped between the disk and the black hole: the former may vary on long time scales, while the latter can only be the sum of all the vertical magnetic flux which has been advected with the gas since the formation of the black hole. An obvious cause for the long-term variability of the magnetic field in the disk would be of course a turbulent dynamo, occurring either in the companion star or in the disk itself; in both cases one could expect (as in the Sun or the Earth) occasional field reversals, for which a time scale of the order of years (corresponding to the long-term variability of GRS 1915+105) would be quite possible.

There would result a dichotomy, depending on the relative signs of the fluxes in the disk and the central hole, analogous to what is seen at the earth magnetosphere/solar wind interface: antiparallel poloidal fluxes are prone to reconnection, and thus presumably relativistic ejections, at the inner disk edge, while parallel fluxes would lead to more complex, less violent physics. Another key ingredient of the scenario is that when the inner region of the disk is weakly magnetized (*i.e.* the ratio $\beta \equiv 8\pi p/B^2$ of the thermal to magnetic pressure is above 1) turbulent accretion can result from the Magneto-Rotational Instability (MRI, Balbus & Hawley 1991), while when β becomes of the order of 1 the MRI stops and the AEI appears.

Details of this scenario can be found in Tagger et al. (2004). A first, and unexpected result, was that a puzzling observation found very naturally an explanation in this scenario: this observation was obtained by Belloni et al. (2000) who, when they described the 12 classes of variability of GRS 1915+105, found that they represented oscillations between three basic states A, B and C (see Figure 3): they observed that all the transitions between these states were allowed, *except* that from C, the low-hard state where the QPO is observed, to B, the high-soft state. Once in C, the source *has to* go through A before it returns to B. In the magnetic floods scenario, this is readily explained by the fact that C is considered as a high magnetization state, whereas B is a low-magnetization one; in order to return from C to B the source needs to destroy magnetic flux by a reconnection event (the spike and ejection, during the β-class cycle), and then spend some time in state A while presumably the radial profiles are restored.

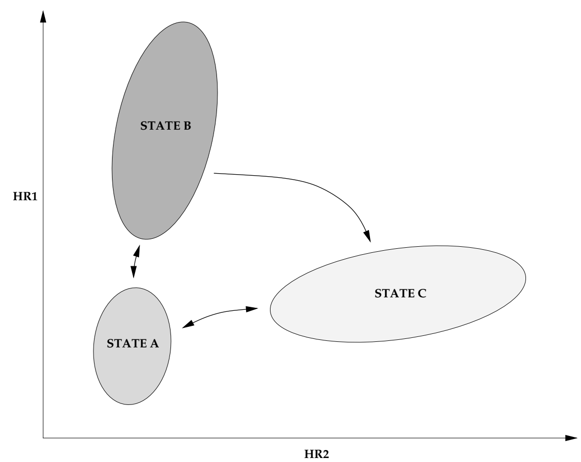

Fig. 3. The three basic states of GRS 1915+105 and their transitions, in a color-color diagram, found by Belloni et al. 2000). In the Magnetic Floods scenario, in state B the inner region of the disk is weakly magnetized, so that accretion can result from the MRI; in state C it is more strongly magnetized, so that the AEI appears and produces the QPO; in state A the magnetization is still strong, but the radial profile of the magnetic field strength does not allow the AEI to appear. The transition from C to B appears to be forbidden.

4. ROSSBY-WAVE INSTABILITY AND HIGH-FREQUENCY QPO

4.1. *Basic description*

The frequency of the AEI is a fraction of the rotation frequency at the inner edge of the disk; this results from the condition that a cavity be established between the inner edge and the radius of corotation (the radius where the wave corotates with the gas). This cavity allows the formation of a standing pattern of spiral waves (see Figure 1). Thus the frequency of the AEI is inherently too low to explain the high-frequency QPOs (HFQPO) observed, with their puzzling 3:2 frequency ratio, in the same sources in their very high or intermediate states (where both the disk and the corona are emitting strongly). Since these frequencies are constant (contrary to the LFQPO) it is commonly admitted that one of them marks the rotation frequency at the MSO, in analogy with the kHz QPO of accreting neutron stars believed to mark the rotation frequency at the inner edge of the disk.

On the other hand, since none of the models presented thus far has convincingly explained these HFQPO, we can wonder whether a family of modes similar to the AEI might be relevant. The idea one can start from is that, if such modes could be found localized very near the MSO, and unstable sometimes with an azimuthal wavenumber $m = 2$ and at other times $m = 3$ (whereas the AEI is localized a bit farther out and favors $m = 1$), the frequency ratio would be readily explained as $\omega = m\Omega(r_{MSO})$ with $m = 2$ or $m = 3$, depending on details of the disk properties (temperature, magnetization...) which may vary with time.

We find that this might very well be the case, given the properties of the Rossby Wave Instability (RWI, Lovelace & Hohlfeld 1978; Lovelace et al. 1999). A schematic description of the RWI is presented in Figure 4.

The RWI is formed of the same spiral and Rossby waves as the AEI, but does not require a reflective inner disk edge to establish a standing wave pattern: let us remind here that in the low/hard state, where the LFQPO is seen, observations show that the conventional optically thick disk extends inward only to an inner radius r_{in}, still away from the MSO. Although we do not know what may exist between this and the black hole (in one form or another, it must be a radiatively inefficient disk) the transition at r_{in} may provide the reflective boundary for the AEI. On

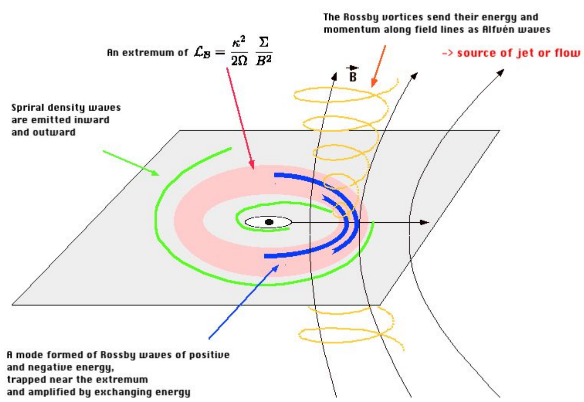

Fig. 4. The RWI is a standing pattern formed of Rossby waves trapped near an extremum of the quantity $\mathcal{L}_B$, and emitting spiral density waves on both sides f this region. As with the AEI, the Rossby waves in turn emit Alfvén waves toward the corona.

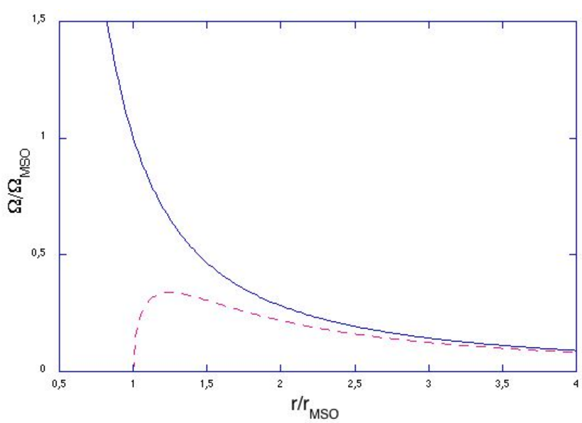

Fig. 5. Radial profiles of Ω (full) and κ (dashed), in the Paczinsky-Witta pseudo-Newtonian potential.

the other hand the disk is believed to extend down to r_{MSO} when the HFQPO is present. The gas plunging inward from this radius passes a sonic point, and it has been shown (Blaes 1987) that this does not provide a reflective boundary.

For the RWI it has been found that a cavity trapping waves can be formed if the radial profile of $\mathcal{L}$ (or $\mathcal{L}_\mathcal{B}$ if the disk is magnetized) presents an extremum. It is this time Rossby waves that are trapped near that extremum, and emit spiral density waves on both sides of it. This condition for an extremum of $\mathcal{L}$ or $\mathcal{L}_\mathcal{B}$ is in fact the application, to a differentially rotating disk, of the classical one (an extremum of vorticity) for the Kelvin-Helmholtz instability of sheared flows (Drazin & Reid 2004).

The RWI has been thus far discussed in standard accretion disks, and thus in practice relies on an extremum of the density profile, since in a keplerian disk $\kappa = \Omega$ and has a monotonous radial profile. However in the accretion disk around a black hole the MSO is defined as a radius (at 3 Schwartzschild radii for a non rotating black hole) where κ vanishes (it is imaginary, implying unstable radial motion, inside the MSO). Starting from that radius κ first increases, and then at larger r decreases as one joins a keplerian rotation curve, so that one has an extremum of κ, and thus of $\mathcal{L}$ close to the MSO, as seen in Figure 5. It is on the existence of that extremum that Nowak & Wagoner (1991) based their discussion of discoseismology. Their g-mode, trapped in the extremum of $\mathcal{L}$, can be identified as the RWI (here we use the classification of Li, Goodman, & Narayan 2003, so that the AEI would be a p-mode), although they seem to have missed the important fact that this mode is strongly unstable, making it unnecessary to find an explanation for its excitation.

The instability mechanism is complex, but essentially the same as that of the Kelvin-Helmholtz instability: in a differentially rotating disk a Rossby wave (which exists in presence of a radial gradient of $\mathcal{L}$) can propagate on either side of its corotation radius (*i.e.* with a frequency Doppler-shifted to the fluid frame, $\tilde{\omega} = \omega - m\Omega$, positive or negative), depending on the sign of $\mathcal{L}$ (or $\mathcal{L}_\mathcal{B}$ if the disk is magnetized). Its energy is accordingly positive or negative. The extremum of $\mathcal{L}$ allows a wave whose corotation radius, where $\tilde{\omega} = 0$, is near that extremum to propagate on *both* sides of it, with energy positive on one side and negative on the other. The wave thus grows by exchanging energy between the two sides of corotation. In doing so it also exchanges matter between the two sides, so that it might also be identified as the application to differentially rotating disks of what is classically known in MHD as an interchange instability[2].

4.2. *First results*

The instability can be conveniently studied analytically or numerically by using the pseudo-Newtonian potential of Paczinsky-Witta,

$$\Phi(r) = GM/(r - r_S).$$

where $r_S \equiv 2GM/c^2$ is the Schwarzschild radius. This mimics the fully relativistic rotation curve, by

[2]Spruit, Stehle, & Papaloizou (1995) discussed interchange instabilities in accretion disks but, without an inner edge or an extremum of $\mathcal{L}$, found instability only for magnetic fields much stronger than equipartition.

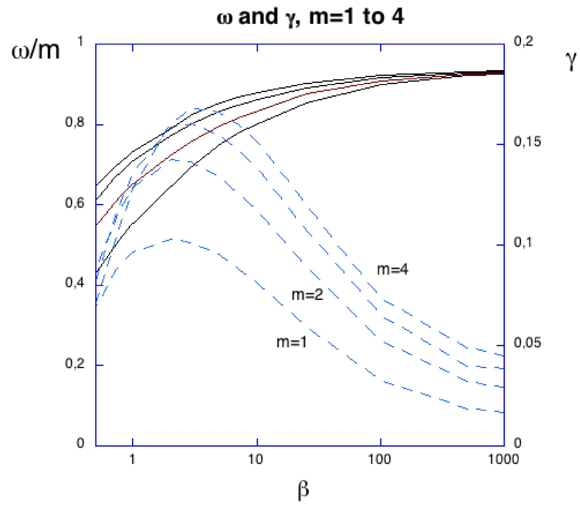

Fig. 6. Frequency (full) and growth rates (dashed) of the RWI, normalized to the rotation frequency at the MSO, for low-m modes, trapped near the MSO in a pseudo-newtonian rotation curve.

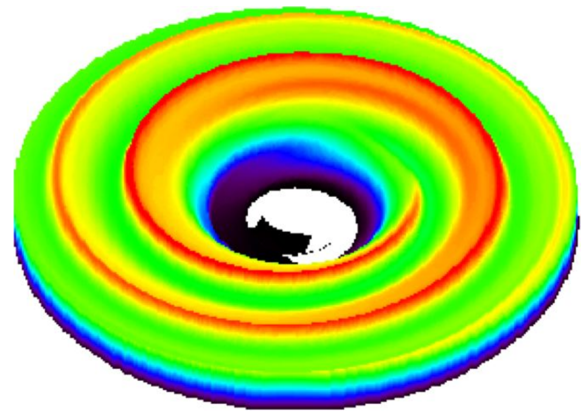

Fig. 7. Surface density in an MHD simulation of a magnetized disk in a pseudo-newtonian potential. The outer boundary of the figure is at $\sim 4\ r_{MSO}$, although the simulation extends to $30r_{MSO}$.

introducing an MSO at $3r_S$, without the additional complexities of a relativistic treatment. However, since the RWI is mostly localized near the MSO, it remains very sensitive to the boundary condition applied at the MSO, and thus to the modelization of the gas flow in this region. For a first approach of the problem, we have applied two models, using a pseudo-newtonian potential:

- The first model relies on a numerical solution of the linearized MHD equations, resulting in an identification of the eigenmodes, and applies at the MSO a reflecting boundary condition, $v_r(r_{MSO}) = 0$. The method we use is the same as that of Tagger & Pellat (1999), reducing the problem to solving for the eigenmodes of a matrix. As shown in Figure 6, it confirms our main expectations: for various values of m and β we find modes with an azimuthal phase velocity (ω/m) very close to $\Omega(r_{MSO})$, and a rather strong growth rate. An encouraging result is that, contrary to the AEI, the $m = 1$ mode is less unstable than the others; this would support our hope to find conditions such that the $m = 2$ or $m = 3$ modes would be the most prominent, but the figure shows that modes with even higher values of m dominate.

- As a second option, we have performed numerical simulations, using the code developed by Caunt & Tagger (2001) which describes an infinitely thin disk in vacuum, modified to include a pseudo-newtonian potential. The code uses a cylindrical grid with logarithmically spaced radial grid points, that allows it to extend to radii far enough that one doesn't need to worry about unwanted effects from the outer boundary. The grid extends typically from $\sim .6$ to $30r_{MSO}$, with $n_r \times n_\vartheta = 256\text{x}128$ grid points, and the MSO is at the 30th radial point. The code also uses the FARGO algorithm (Masset 2000), which accelerates computations in differentially rotating disks. The inner boundary is transparent, letting the gas flow freely to the center. Thus after a few rotation times the flow establishes a "plunging region", including a sonic point. With this very different boundary condition the simulations show a strong mode developing near the MSO, as shown on Figure 7, but this time it is an $m = 1$.

These are only preliminary results; they confirm that the RWI could produce a strong QPO from the inner boundary of the disk. This is a very robust result since it relies only on the dynamical property associated with the existence of an MSO, remaining even in an unmagnetized disk, and for any reasonable radial profile of the density and magnetic field. The linear analysis and the non-linear simulation give contradictory results on the most unstable wavenumber, because they use different boundary conditions. But it may well be that the real boundary condition is more complex. In particular let us remember that the discussion in Section 3.3 about the "Magnetic Floods" scenario has led us to attribute a key role to the poloidal magnetic flux trapped in the central region, between the disk and the black hole. Indeed, if there is such a trapped flux, it must be organized in a force-free structure such as the one discussed in the Blandford-Znajek mechanism (Blandford & Znajek 1977). This structure is believed to be generated by a current ring near the inner edge of the disk, and one can expect that it would apply, to perturbations in the disk, a boundary condition much more complex than the ones used here. In that case finding that the most unstable modes would be the $m = 2$ and $m = 3$ would not be a surprise. This possibility would provide a convincing explanation for the HFQPO, and connect it with a broader view of the evolution of black-hole binaries. It will be explored in future work.

5. THE FLARES IN THE GALACTIC CENTER

We have recently (Tagger & Melia 2006) presented another possible application of the RWI, to explain the flares observed in IR (Genzel et al. 2003) and X-rays (Bélanger et al. 2005) in Sagittarius A*, the massive black hole at the center of the Galaxy. Our view of this object has made considerable progress in recent years (see e.g. Melia & Falcke 2001); its very low emission seems to be explained by the numerous winds from neighbouring stars, sweeping the region and preventing the formation of a "conventional", extended disk. On the other hand, strong flares occur, interpreted as resulting from the occasional accretion of clumps of magnetized plasma captured from these winds (Igumenshchev & Narayan 2002). This gas has low angular momentum and circularizes in the disk at relatively small radii, typically 10 to 10^3 Schwarzschild radii. The flares are quite short (a few hours) and marked by a few quasi-periodic oscillations with a period of $\sim 17 - 20$ minutes, close to the expected rotation frequency at the MSO for a $\sim 3.6\ 10^6 M_\odot$ black hole.

Our explanation starts from the assumption that indeed a blob of gas has "rained onto" the disk and formed a circular bump at a radius of a few r_{MSO}. In these conditions $\mathcal{L}_B$ has two extrema in the disk: one, due to κ, near the MSO as before, and another one, due to the surface density, where the blob has circularized. This results in two families of Rossby-Wave Instabilities, at the MSO and at the bump, which cause a very fast accretion of the blob.

Using the same code we have found that the accretion flow through the MSO shows a brief episode of strong accretion, lasting for a few rotation times and thus compatible with the duration of the flares. Figure 8 shows the surface density in the disk, at the moment when the circular blob (at 4 r_{MSO} in this case) gets disrupted by the instability. Furthermore the accretion rate at the inner edge shows a quasi-periodic modulation, also very compatible with the observed signal. This —which does not depend much on our initial conditions, including the initial location of the blob— is shown in Figure 9.

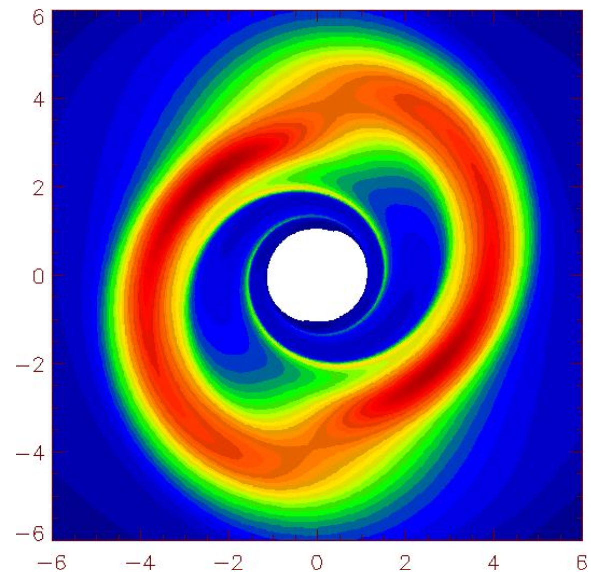

Fig. 8. The surface density in the disk in our simulation of the Galactic Center disk. The snapshot is taken at the time when the blob, initially located at 4 r_{MSO}, starts getting disrupted by the instability (here an $m = 2$).

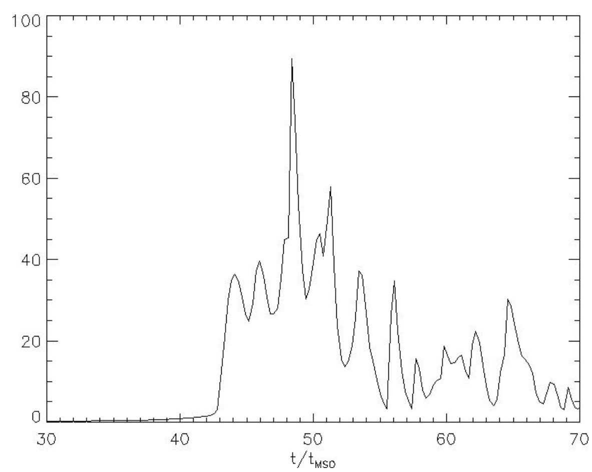

Fig. 9. The accretion flow through the MSO in our simulation of the Galactic Center disk. Both the duration of the flare and the quasi-periodic behavior are similar to the observed ones.

The quasi-periodic modulation cannot be explained directly by a non-axisymmetric perturbation, once averaged over ϑ. We rather believe that it is the manifestation of an axisymmetric ($m = 0$) mode, excited non-linearly by the development of the RWI.

Let us finally mention that one can expect, as for the AEI, that a large fraction of the energy extracted from the disk by the RWI can be emitted upward as Alfvén waves. This would explain that during the flares the emission both in X-rays and IR is believed to result from a Synchrotron-self-Compton process (Eisenhauer et al. 2005; Liu & Melia 2001), meaning that more energy is received from the corona than from the disk.

6. CONCLUSION

Since the discovery of the Magneto-Rotational Instability (Balbus & Hawley 1991) it can be considered that the main source of accretion in disks has been identified. The MRI causes a turbulent transport with all the necessary properties. However much remains to be explained: in particular the connection between this and jets, and also the various QPO observed in X-ray binaries. The course of our work has shown that another family of instabilities of magnetized disks should be considered. This family, which includes both the AEI and the RWI, is closely related to the spiral instability of self-gravitating disks and to the Papaloizou-Pringle instability.

The AEI and the RWI are both normal modes, producing coherent, low wavenumber structures rotating in the disk and thus well adapted to produce QPOs — although the mechanism leading from a non-axisymmetric structure in the disk to the pulsed observed emission is not understood yet. They are formed of the same building blocks, spiral density waves and Rossby waves, propagating in the disk and coupled by differential rotation which allows an exchange of energy and momentum between them. They both extract energy from the disk (thus causing accretion) and transport it as wave energy, rather than dissipate it locally as commonly assumed in the α-disk model. Furthermore they can redirect to the corona as Alfvén waves a significant fraction of that energy, where it could feed the jet — although the mechanism by which the wave energy can be deposited in the corona (rather than traveling to infinity) also needs to be elucidated. But these properties explain that the instabilities are seen in states where the disk emission is weak or absent, and the coronal emission is strong. This applies to all the applications we have discussed here,the LFQPO, the HFQPO, and the flares at the Galactic Center.

The existence of the AEI and RWI depend on boundary conditions at the inner disk edge: the AEI needs a reflecting boundary, which may be provided (in the low/hard state of microquasars) by the transition between the optically thick disk and the radiatively inefficient inner region. The RWI depends on the existence of an extremum of a certain quantity ($\mathcal{L}$ or $\mathcal{L}_{\mathcal{B}}$); this can be produced, either near the MSO or where the density profile in the disk presents an extremum. In the first case the azimuthal wavenumber appears to depend on the boundary condition used.

It is remarkable that from both these points of view — the "Magnetic Floods" scenario starting from the explanation of the LFQPO by the AEI, and the ability of the RWI to explain the HFQPO— we get to the same point: both point to the key role played by the existence and the nature of the central magnetic structure, holding the poloidal magnetic flux trapped in the central hole between the disk and the black hole. Taking this into account will be the object of future work.

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