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A POSSIBLE INSTABILITY ORIGIN FOR THE FLARES IN SAGITTARIUS A*: LINKING SIMULATIONS AND OBSERVATIONS

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Abstract. While flares in the submm, near-IR and X-ray domains are regularly detected from Sagittarius A* (Sgr A*), the supermassive black hole at the center of our galaxy, no model has yet gained wide acceptance. Here we focus on structures originating from the wind of close-by massive stars or from the partial disruption of a comet/cloud/star and we study how instabilities occuring in those structures could produce an accretion burst and an associated observable flare.

Using NOVAs, composed of 3D general relativistic (GR) magneto-hydrodynamical (MHD) and GR ray-tracing codes, we aim to investigate how a post-disruption circularized annulus of gas hosts the development of the Rossby Wave Instability. We first show that the subsequent accretion event indeed produces an observable flare. Then, we look how this population of flares behaves with respect to SgrA* flares in the parameter space. In particular, we show how the annulus properties in terms of mass and spatial extent (partly inherited from its parent object, star or cloud) can reproduce the variety of observed flare shapes.

Keywords: Sagittarius A*, flare, submillimeter

1 Introduction

Theoretically, accreting Black Holes (BH) show us how matter behaves in a strong gravitational field. Observationally, they power among the most energetic accretion/ejection processes in the Universe, whose exact properties remain unknown. While not being as active as many supermassive BHs, the galactic supermassive BH Sgr A* offers a unique possibility for observing and understanding those objects: it has the largest angular size of any BH observable from Earth and it powers frequent (typically one per day) X-ray, near infrared and submm flares, i.e. sudden increases in brightness above the quiescent level, often at the same time or with a short delay. As the emission is estimated to originate from only a few gravitational radii from the BH (see e.g., GRAVITY Collaboration et al. 2018), those flares provide insights on the nearest region to the BH horizon.

The mechanism and the emitting process behind those flares remain debated, even though they are ubiquitous in the observations of Sgr A*. Indeed, a model should be able to reproduce the flare energetics as well as the lightcurve properties (duration, amplitude, shape. . .) and correlations between those properties over the electromagnetic spectrum. The typical duration is of the order of the orbital period and the amplitude can reach $\sim$70 times the quiescent level. Moreover, a single flare event can exhibit several local maxima before turning back to quiescence, something we will refer to as the flare "multiplicity". Overall, a model should account for the diversity of flare shapes observed while relying only on one physical phenomenon. We address in particular this problem here.

Estimates on the energetics of flares led to consider accretion of asteroids/comets as a possible explanation. These so-called partial/total tidal disruption events (hereafter, TDEs) may produce a ring-like structure of magnetized debris stream falling onto the BH (see Bonnerot & Stone 2021 and refs. therein). Such structures

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would naturally give rise to the Rossby Wave Instability (RWI, Lovelace et al. 1999, see below). Indeed, the presence of an extremum of density in the ring-like structure will lead to the extremum in vortensity required by the RWI. In this study, we follow the RWI developing on this ring, building on previous studies (see Tagger & Melia 2006 and Falanga et al. 2007) that have shown it to match the flare duration, amplitude and modulation observed in several long flares (Bélanger et al. 2006). Our ultimate goal is to link the pre-flare properties (i.e. the ring and before that, the disrupted object) to the flare properties.

To that end, we use the NOVAs pipeline. NOVAs includes the GR-MHD version of the GR-AMRVAC code (Casse et al. 2017) which will allow us to expand in full GR the work done by Falanga et al. (2007) in pseudo-Newtonian gravity. More importantly, we will use NOVAs to produce synthetic observations with the GR ray-tracing code GYOTO* (Vincent et al. 2011). In fact, photons emitted close to the BH can reach the observer with a delay as large as half an orbital timescale at the LSO (Vincent et al. 2013), producing a secondary image (see also Casse et al. 2017 for the importance of including GR in the ray-tracing step of a BH disk). This two-steps process will allow us to obtain observables and to directly compare them with observations.

2 GRMHD simulations of the Rossby Wave Instability

The RWI is a good candidate to explain Sgr A* flares because it provides a natural mechanism to produce accretion bursts, as we will show now. Indeed, the RWI develops at the location of an extremum in vortensity (i.e. specific vorticity) or magneto-vortensity (Tagger & Varniere 2006), defined as (Tagger & Pellat 1999)

$$L_{\mathrm{B}} = (\nabla \times \mathbf{v})\,\frac{\Sigma}{B^2}, \tag{2.1}$$

where $\mathbf{v}$ is the velocity vector, Σ is the surface density and B is the magnetic field strength. When a post-TDE stream circularizes, it naturally develops an extremum in vorticity as the centrifugal acceleration builds the equilibrium around the density extremum. Thefore, the RWI will naturally develop on this ring and lead to an accretion burst, which was proposed earlier to produce an observable flare. The RWI has been studied in various astrophysical contexts because the aforementioned extremum is naturally present at the last stable orbit (LSO) of differentially-rotating disks, which makes it an elegant model for explaining the high-frequency quasi-periodic oscillations of microquasars (i.e. accreting stellar-mass BHs).

Here are the initial conditions of our simulations, consisting of a background disk with an additional ring structure. The background disk density profile follows a power-law of index $-3/4$, and the disk is initially threaded by a radial and vertical magnetic field with a plasma beta $\beta \gg 1$, consistent with a very weakly magnetized medium. On top of this background disk, the ring structure corresponds to an axisymmetric bump whose density is given by

$$\Sigma_{\mathrm{b}}(r) = \epsilon_{\mathrm{b}} \exp\left(-\left(\frac{r - r_{\mathrm{b}}}{\sigma_{\mathrm{b}}}\right)^2\right) \tag{2.2}$$

where r is the radius with respect to the central BH. We consider simple ring properties such as its amplitude ϵ_{b}, its width σ_{b} and its position r_{b}. The bump vertical magnetic field is defined similarly. We explore ring magnetization levels from weakly magnetized ($\beta{\sim}5$) to fully magnetized ($\beta{\sim}1$). Those ring properties are inherited from the disrupted object mass, magnetization and angular momentum.

As shown in the density map of the left panel of Fig. 1, we see the RWI developing on the ring-like structure. Its behaviour agrees with the studies reported in the literature. Furthermore, as can be observed, the RWI leads to the formation of overdensities. The number of those overdensities is linked to the multiplicity of modes of the instability, which relies on local conditions (Varniere et al. 2019) and could possibly create several pics within a flare event (i.e. without the flux returning to the quiescent level). Hence, the number of pics would vary between different flares. In the simulation, we observe that the accretion is no longer axisymmetric and occurs via the episodic accretion of overdensities.

Then, we computed the frequency-integrated flux after the ray-tracing step and obtained the lightcurve displayed in the right panel of Fig. 1. For this work, we considered the frequency band $10^9 - 10^{15}$ Hz, covering the submm and near-infrared domains. We assume that the flares in those frequency bands arise from synchrotron

*Freely available at `http://gyoto.obspm.fr`

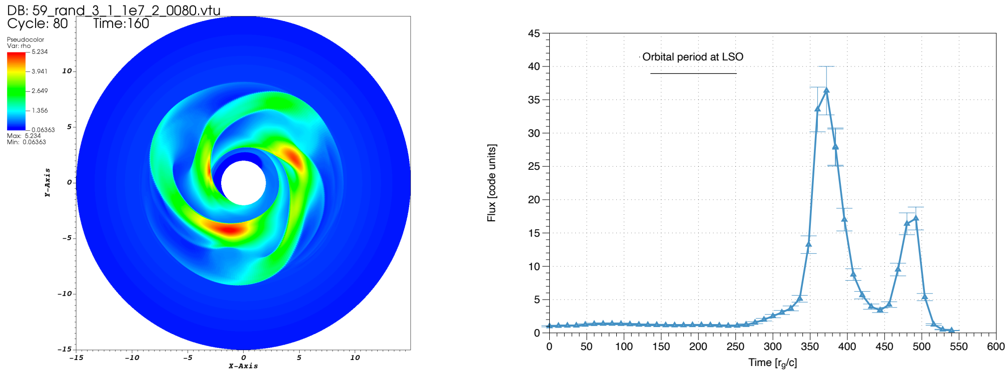

Fig. 1. Left: Density map of the RWI developing on the ring in the non-linear regime. **Right:** Corresponding light curve. Time has been expressed in r_g/c, where r_g is the gravitational radius and c is the speed of light.

emission with a κ distribution (with $\kappa = 5.5$). This lightcurve shows us that, as seen from an observer, the aforementioned accretion bursts indeed translate into a flare event. Moreover, the duration of this flare is roughly the orbital period, in agreement with the observational constraints.

3 Reproducing the flare variability

Left panel of Fig. 2 shows the concatenated lightcurve of Sgr A* in the K-band (2.2μm) as seen by VLT/NACO and Keck/NIRC2 (Fazio et al. 2018). As can be seen, flares have no typical shape: a Gaussian fit is not always satisfactory and they are not symmetric. A flare model should account for this.

Here, we investigate how the RWI can reproduce flare properties. Using the ring amplitude and width (i.e. the mass, magnetization and angular momentum of the disrupted object), we show in the right panel of Fig. 2 it is already possible to reproduce this variety of behaviors. All simulated flare durations are of the order of the orbital period at the LSO. This confirms the RWI as a good candidate to explain the variety of flare behaviors.

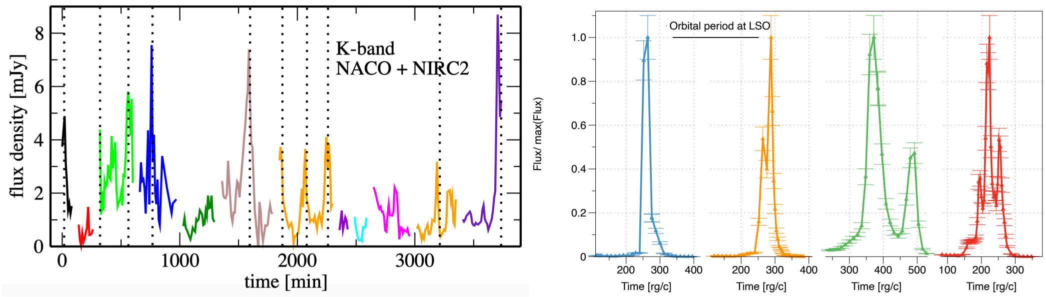

Fig. 2. Left: Concatenated lightcurve showing the near infrared flares of Sgr A* (Credits: Fazio et al. 2018 and Zhiyuan Li) exhibiting a variety of structures. More than one flux extremum can be seen in a single flare event. **Right:** Synthetic light curves reproducing the variety of observed flare shapes. We have varied the ring amplitude and witdh. For readability, fluxes are normalized by the maximal flux.

As briefly mentioned in the introduction, a single flare event can have a multiplicity of peaks (visible in the left panel of Fig. 2). A physical interpretation could be that multiple clumps have been accreted in a short amount of time, indicating that they could come from the same density structure. This is an additional constraint for a flare model, which we study next.

As shown in the right panel of Fig. 3, for a given set of parameters, the RWI is capable of reproducing qualitatively the multiplicity reported in the study of Hamaus et al. (2009) (left panel of Fig. 3). So far, varying the ring amplitude and width only, we get a flare multiplicity in the range [1;4] as it is the one that could be detected at those timescales, similar to the variety of multiplicities observed. Let us note though that, depending on the temporal resolution and the instrumental noise, detecting multiplicity within a flare can be challenging. Therefore, comparing the multiplicity of an observed flare with that of a synthetic flare - whose temporal resolution can be much finer - is not straightforward. Nonetheless, the presence of such multiple peaks confirms the relevance of the RWI model, as several overdensities formed by the instability get accreted.

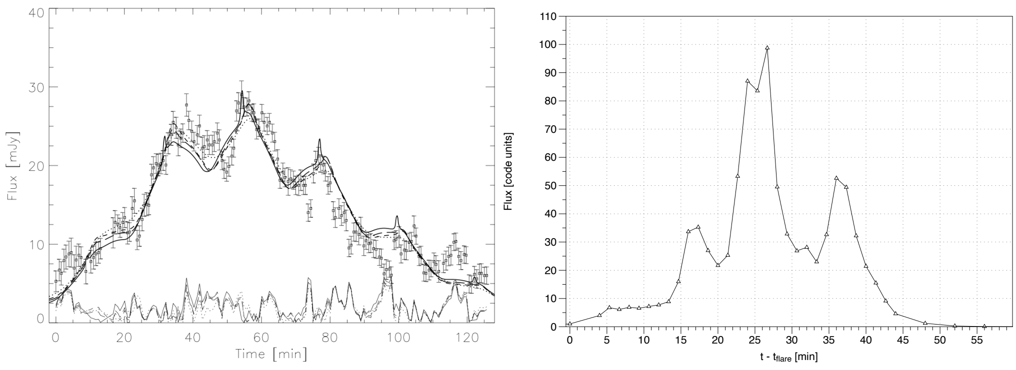

Fig. 3. Left: Observational light curve in the near-infrared range (credits: Hamaus et al. 2009). **Right:** Synthetic light curve of the frequency-integrated flux (in code units) reproducing qualitatively the multiplicity exhibited by the observational light curve. Time has been expressed in minutes for direct comparison with observations. Flare durations agree within a factor of two.

4 Conclusions

We followed the development of the Rossby Wave Instability on a ring-like structure following a TDE. As a first step we focused on the ring amplitude (in terms of magnetic fields and density), spatial width and position, whose combination points to the mass, magnetization and angular momentum of the disrupted object.

Our preliminary results show this model is able to produce a variety of flare behaviors and so-called "multiplicity" (i.e. number of peaks detected within a given flare) such as those observed in the flares of Sgr A*. While the presented lightcurves originate from spectra dominated by the submm emission, observable with the Very Large Array (VLA), our next step is to distinguish between this emission and the near-infrared emission to be then compared with the observations of GRAVITY. Furthermore, preliminary estimates on the dimensioned flux, to test the observability of our synthetic flares, are under study and confirm that they can reach the observed level (5 mJy in the GRAVITY band).

While we focus here on the flares of Sgr A* following a partial/total TDE, all the results presented here could be applied to other TDEs.

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