10.1515/astro-2017-0135

Baltic Astronomy, vol. 25, 304–309, 2016

A QUASI-STATIONARY TWISTED DISK FORMED AS A RESULT OF A TIDAL DISRUPTION EVENT

M. Xiang-Gruess[1], P. B. Ivanov[2,3] and J. C. B. Papaloizou[3]

[1] *Helmholtz-Institut für Strahlen- und Kernphysik, Nussallee 14-16, 53115 Bonn, Germany*

[2] *Astro Space Centre, P. N. Lebedev Physical Institute, 84/32 Profsoyuznaya st., Moscow, 117997, Russia*

[3] *DAMTP, University of Cambridge, Wilberforce Road, Cambridge CB3 0WA, UK*

Received: 2016 September 27; accepted: 2016 October 17

Abstract. In this note we briefly review the main results of our recent study of the formation of misaligned accretion disks after the tidal disruption of stars by rotating supermassive black holes. Since the accretion rates in such disks initially exceed the Eddington limit they are initially advection dominated. Assuming the α model for the disk viscosity implies that the disk can become thermally unstable when the accretion rate is comparable to, or smaller than, the Eddington value, while still being radiation pressure dominated. It then undergoes cyclic transitions between high and low states. During these transitions the aspect ratio varies from ~ 1 to $\sim 10^{-3}$, which is reflected in changes in the degree of disk misalignment at the stream impact location. For maximal black hole rotation and sufficiently large values of the viscosity parameter, $\alpha \gtrsim 0.01-0.1$, the ratio of the disk inclination to that of the initial stellar orbit is estimated to be 0.1–0.2 in the advection dominated state, while reaching order unity in the low state. Misalignment decreases with decrease of α, but increases as the black hole rotation parameter decreases. Thus, it is always significant when the latter is small.

Key words: accretion disks – hydrodynamics – galaxies: supermassive black holes

1. INTRODUCTION

A tidal disruption event (TDE) occurs when a star approaches sufficiently close to a supermassive black hole that it is ripped apart by tidal forces. Its orbit must take it within the so-called tidal disruption radius, R_{T}. This radius is such that the mean mass density equal to that of the black hole, assumed to be enclosed within a sphere of radius R_{T}, is equal to that of the star. The ensuing tidal disruption results in an accretion disk around the black hole being formed from the stellar gas. This in turn gives rise to a luminous source of radiation. As was pointed out by Lacy et al. (1982) and Rees (1988), when the stellar orbit is assumed to be parabolic and tidal forces totally disrupt the star, approximately one half of the stellar material gains positive orbital energy and is expelled from the system, while the remainder attains negative energy (or equivalently positive binding energy) and, accordingly, becomes gravitationally bound to the black hole. Gas elements comprising the bound material will in general have binding energies ranging between some largest absolute value and zero. Accordingly, they return to periastron at different times after the TDE, forming a stream of gas that first arrives at periastron when time $\sim P_{\rm min}$ has elapsed after the star was tidally disrupted (see, e.g., Rees 1988). Supposing that the amount of mass occupying any small binding energy interval of fixed extent is approximately uniform, it is easy to estimate that the mass flux from this stream should be $\propto t^{-5/3}$ when $t \gg P_{\rm min}$ (see, e.g., Lodato et al. 2009 and references therein). At times on the order of $P_{\rm min}$, the stream starts to intersect itself near periastron as a result of, for example, Einstein precession, giving rise to the formation of strong shocks. These shocks convert the kinetic energy of the stream into heat, which is later radiated away. This process leads to the formation of a gaseous torus around the black hole, which later spreads to an accretion disk through the action of an effective viscosity resulting from gas turbulence. Assuming that the black hole is non-rotating, the mid plane of the accretion disk will coincide with that of the initial stellar orbit. However, in the case of a Kerr black hole, the Lense-Thirring force acts to drag it to coincide with the black hole's equatorial plane. On the other hand, the orbital plane of the stream is the same as that of the initial stellar orbit. This is in general expected to be inclined with respect to the black hole's equatorial plane with an inclination angle on the order of unity. Accordingly, the stream material arriving in the region close to the initial periastron, after accretion disk formation and assumed relaxation to the equatorial plane, will impact the disk obliquely, pushing it out of the black hole's equatorial plane. Thus, there is a possibility that the disk is inclined with respect to the black hole's equatorial plane at radii on the order of the stream impact radius. In addition, the combined action of black hole rotation and oblique stream impact leads to a non-trivial dependence of the disk tilt and twist angle on the distance from the black hole. This could potentially be used as a diagnostic for determining the black hole mass and angular momentum as well as to probe the physical conditions in the accretion flow.

It is the purpose of this note to briefly review our recent analysis of the conditions under which the inclination angle at the stream impact radius can be large. A more extended discussion of the results obtained as well as a description of our methods is given elsewhere (see Xiang-Gruess et al. 2016). As explained in that paper, we tackle the problem using a combination of analytic and numerical techniques. We employ the linear theory of twisted accretion disks (e.g., Papaloizou & Pringle 1983; Papaloizou & Lin 1995), three-dimensional numerical simulations with an appropriately modified smoothed particle hydrodynamics (SPH) code GADGET-2, and one-dimensional numerical scheme based on the finite difference code NIRVANA in order to study the evolution of a flat disk model taking account of both gas and radiation pressure together with the mass input from the stream to the disk. This flat disk model provides model data for an equation enabling the determination of the disk tilt angle β and twist angle γ, derived from linear theory, hereafter referred to as the twist equation. Note that this equation is analogous to that considered by Ivanov & Illarionov (1997) and Demianski & Ivanov (1997), but modified by the addition of a source term accounting for the action of the stream. It is solved in the quasi-stationary approximation (see, e.g.

Ivanov & Illarionov 1997). We show that when $\alpha \gtrsim 0.1$ and black hole rotation is close to maximal, the typical inclination angles of the disk are on the order of $\sim 0.1 - 0.2$ times the stream inclination angle at the initial advection dominated stage[1]. However, the inclination angle becomes larger as the disk aspect ratio decreases as a result of transitions from being advection dominated to being radiative, which take place when the mass flow in the disk becomes smaller than the Eddington value. The inclination angle exhibits a limit cycle like behavior when the standard α-model is used (see, e.g., Abramowicz et al 1988). During these transitions, inclination can grow to values close to that of the stream. Furthermore, disk inclination gets larger for smaller black hole rotation at all stages of the evolution of the disk.

2. A COMPARISON OF ANALYTIC RESULTS AND SPH SIMULATION

Let us briefly discuss numerical simulations based on the SPH method used in this study. We performed SPH simulations of the evolution of a disk which is impacted by a gaseous stream resulting from the tidal disruption of a star. We used a modified version of the publicly available GADGET-2 code. This is a hybrid N-body/SPH code capable of modeling both a fluid and distinct massive bodies that interact with it. In our case we incorporate a rotating black hole of fixed mass M. Relativistic effects are taken into account by adding effective forces acting within classical Newtonian description. We considered both 'star' particles and 'stream' particles, which evolve separately before the first stream particles return to periastron. After this stage all the particles are allowed to interact. In so doing, stream particles are converted into disk particles. The total number of particles involved in the simulations presented here is 4×10^5 with 50% of these originating in the stream and 50% in the disk. The disk aspect ratio δ and the viscosity parameter α are both approximately equal to 0.1 in these simulations. In Fig. 1 we show the dependence of the disk inclination angle at the stream impact location on time t expressed in units of the inverse Keplerian angular frequency at periastron of the stellar orbit, $\Omega_{\rm p}^{-1}$. The solid and dashed curves represent SPH results for the black hole rotation parameter $a = 1$ and 0.1, respectively, while the dotted and dot-dashed curves are their respective counterparts obtained by solving the analytic twist equation. This is solved numerically with background model parameters adopted from SPH simulations. We see that the analytic and SPH approaches are in agreement in finding that the case with $a = 1$ becomes quite closely aligned whereas the case with $a = 0.1$ maintains significant misalignment. Thus we can expect that for disks with $\delta \sim 0.1$ and other parameters appropriate to the TDE we consider, significant misalignments are to be expected for some systems. One can also see from Fig. 1 that there is a good agreement between the semi-analytic curves and those derived from SPH simulations corresponding to the case $a = 1$. The typical deviation is on order of 20 per cent. When $a = 0.1$, there is a factor of $1.5-2$ discrepancy for times $\lesssim 10^4 \Omega_{\rm p}^{-1}$, which can perhaps be attributed to slower relaxation of the twisted disk to a quasi-stationary configuration in this case. This is not unexpected as the time scale associated with attaining alignment in the absence of the stream is expected to be longer for smaller values of the

[1] For smaller values of α the inclination angle is estimated to be even smaller during this stage.

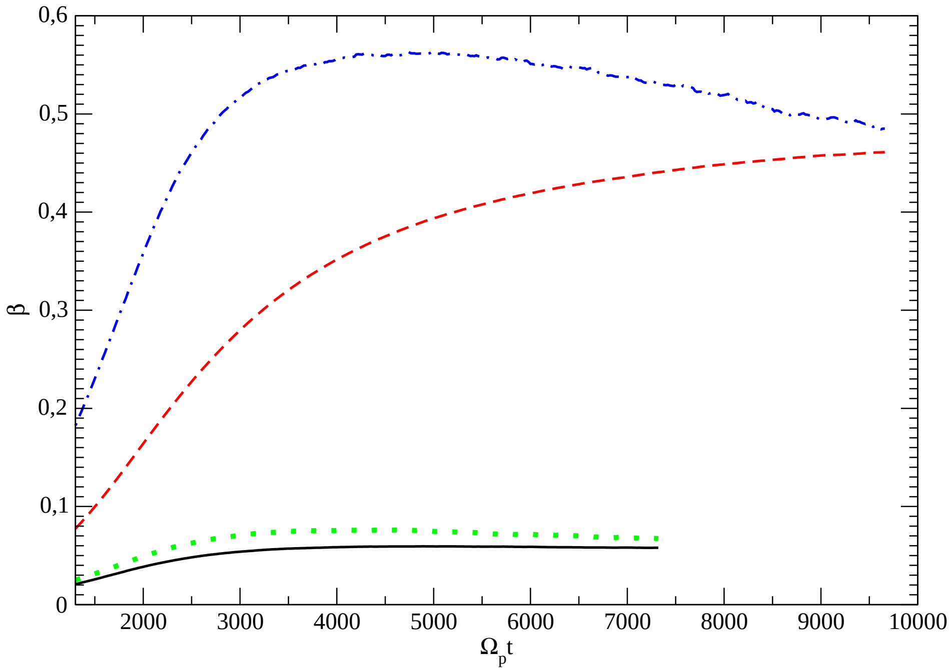
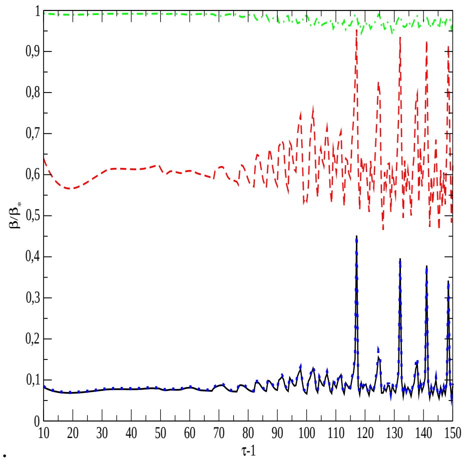


Fig. 1. Time dependence of the inclination angle β, in radians, at the stream impact position $r = 1$. See the text for a description of particular curves.

rotation parameter a. However, the discrepancy becomes quite small at later times with a typical difference on the order of 5 per cent.

3. RESULTS BASED ON THE FINITE DIFFERENCE NUMERICAL SCHEME COMBINED WITH SOLUTIONS OF THE TWIST EQUATION

The SPH simulations cannot take into account many important ingredients of the problem as well as be evolved sufficiently long enough. Therefore, we performed grid-based simulations of a flat α-disk with the equation of state being a mixture of ideal gas and radiation and the source of mass supply at the stream impact radius. Simulations were evolved several tens of $P_{\rm min}$, through the advection dominated stage and the beginning of the transition to a radiative disk with a small aspect ratio, $\delta \sim 10^{-3}$, which is accompanied by the limit cycle behavior between transient 'high' advection dominated stages with $\delta \sim 1$ and low radiative stages with $\delta \sim 10^{-3}$ as a result of the development of thermal instability in radiative, radiation pressure dominated α-disks. The surface density and the aspect ratio obtained from these simulations were used as input parameters for solutions of the twist equations. Due to numerical limitations only rather large values of $\alpha = 0.3$ and 0.1 were considered. In Fig. 2 the solid, dashed and dot-dashed lines illustrate solutions of the twist equation for prograde rotation of the black hole with $a = 1$, 0.1 and 0.01, respectively. From these results it is apparent that smaller black hole rotation leads to larger disk inclination, as expected. In addition, the time averaged values of the inclination for $a = 0.1$ and $a = 1$ are similar in magnitude to



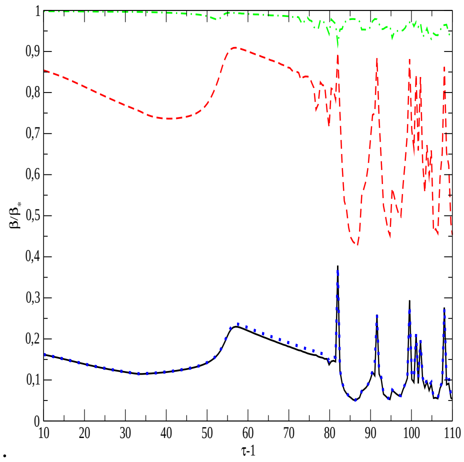


Fig. 2. *Left-hand panel.* Inclination angle β in the units of the stream inclination, β_*, at the stream impact position $r = 1$ as a function of time $\tau = t/P_{\rm min}$ shown for the grid-based model with $\alpha = 0.3$. See the text for a description of different particular curves. *Right-hand panel*: the same as left-hand panel, but for $\alpha = 0.1$.

those found for the SPH simulations of a disk with $\delta \sim 0.1$ throughout as discussed above. The dotted curves illustrate the case of retrograde rotation with $a = -1$. Since the results found for retrograde rotation with a smaller absolute value of a practically coincide with those obtained for its prograde counterpart, they are not shown. The results illustrated in Fig. 2 indicate that values of the scaled inclination are quite substantial for our models at all times, being on the order of 0.1 for $a = 1$ and larger for smaller values of rotational parameter. The high-state super-Eddington regime of accretion corresponds to $\tau < \tau_{\rm crit} \approx 80 - 100$. When $\tau > \tau_{\rm crit}$, a transition to the low state occurs, however, since there is a continuing supply of mass from the stream and radiation pressure is important, the condition for the development of thermal instability will become satisfied, with the result that the disk undergoes a sequence of transitions between high and low states. The inclination angle changes quite dramatically in the course of these transitions being on the order of the maximal value at low states and dropping to values on the order of $(0.05 - 0.1)\beta_*$ during the intermittent high states. These sharp changes in disk inclination are related to sharp changes of the aspect ratio δ during transitions.

4. CONCLUSIONS

In this note we briefly reviewed our results on the interaction of an accretion disk around a rotating black hole and a stream of gas hitting the disk at some oblique angle. Both the disk and the stream are assumed to have originated from the tidal disruption of a star of solar mass and radius by a black hole. We employed both analytic and numerical methods in our study. A more detailed exposition of our results is given in Xiang-Gruess et al. (2016). As a result of the interplay between the action of the Lense-Thirring force determined by the black hole rotation and the angular momentum supply from the stream to the disk, the latter becomes twisted with the inclination angle with respect to black hole equatorial plane, β, being in general a function of radius and time. We calculated a sequence of quasi-stationary twisted disk configurations and so found the dependence of β at the stream impact radius on time. We found that during the advection dominated stage the typical disk inclination, β, is of order of $0.1\beta_*$, where β_* is the stream inclination, and we consider the black hole rotation close to maximal and $\alpha \sim 0.1$. The disk inclination grows to values $\sim 0.4\beta_*$, when the disk experiences transitions to low radiative states. For smaller black hole rotations these inclinations are larger, while they become smaller for smaller values of α.

Thus, measuring the inclination could lead to information about black hole rotation, the disk viscosity parameter α, and the possibility for the disk to experience thermal instability during its transition from advection dominated to radiative stage. Note that during these transitions the assumption that the twisted disk is quasi-stationary may be broken. In such a situation time-dependent calculations of the evolution of the disk tilt and twist will be important. This will be the subject of future work.

ACKNOWLEDGMENTS. M. Xiang-Gruess acknowledges support through Leopoldina fellowship programme (fellowship number LPDS 2009-50). Simulations were performed using the Darwin Supercomputer of the University of Cambridge High Performance Computing Service, provided by Dell Inc. using Strategic Research Infrastructure Funding from the Higher Education Funding Council for England and funding from the Science and Technology Facilities Council. MXG also acknowledges the computing time granted (NIC project number 8163) on the supercomputer JUROPA at Jülich Supercomputing Centre (JSC). PBI was supported in part by Programme 7 of the Russian Academy of Sciences and in part by Russian Foundation for Basic Research (grants No. 15-02-08476 and 16-02-01043).

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