

STAR-DISK COLLISIONS IN THE GALACTIC CENTER

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STAR-DISK COLLISIONS IN THE GALACTIC CENTER

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¹Carl was once a Tech student pursuing physics until he found a deeper love for biology.

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SUMMARY

Recent observations of the Galactic Center (GC) have revealed that there is a relative paucity of Red Giant (RG) stars within the central parsec. However, these observations conflict with our current theoretical understanding. We would expect the GC to have formed a segregated cusp of late-type stars. A recent explanation for this theoretical issue is that the outer envelopes of RG stars may have been stripped due to collisions with a fragmenting accretion disk in the GC. Both numerical and analytic models of star-disk collisions have been considered by several authors prior to this work, but a majority of the literature has focused on either the envelope stripping of a Main-Sequence (MS) star or other phenomena associated with this particular interaction. Here we investigate the envelope stripping of a RG star of radius $R_* = 10R_\odot$ and mass $M_* = 1M_\odot$ colliding with the dense regions of a fragmenting disk. From our simulations, we are able to conclude that a RG star is likely to be stripped of its outer envelope and, occasionally, disrupted.

Chapter I

INTRODUCTION

The contact interaction of stars from a nuclear cluster with an accretion disk surrounding a super massive black hole (SMBH) is an inevitable and common phenomenon. In particular a star from the nuclear cluster will often have an orbital trajectory which intersects the plane of the accretion disk. These so-called star-disk collisions are expected to play an important role in the appearance and evolution of the nuclear region. Thus, star-disk collisions have been studied by many authors for various reasons and are proposed to give rise to several important (observational) phenomena.

The two main structures in galactic nuclei that may be altered due to star-disk collisions is the central accretion disk surrounding the SMBH and the nuclear star cluster (NSC). Star-disk collisions have the potential to influence the dynamics and evolution of an accretion disk through heating (Perry and Williams, 1993), imposing viscous drag on the accretion disk (Ostriker, 1983), and the removal of angular momentum from the disk (Norman and Silk, 1983). Stellar impacts can also result in the appearance of bright hot spots on the accretion disks surface (Zentsova, 1983) and may be responsible for the origin of the broad lines in quasars (Zurek et al., 1994).

In a similar fashion, the structure and dynamics of a NSC can be affected by a neighboring accretion disk surrounding the central SMBH. The general understanding is that stars from the nuclear cluster will lose their orbital energy and angular momentum after each collision causing the systematic decay of stellar orbits around the central SMBH (Rauch, 1995; Karas and Šubr, 2001). Hence, we expect the density of stars near the SMBH will steadily increase until other processes kick in, such as tidal disruption due to the SMBH and star-star collisions which would tend to

scatter stars from the central region (Vilkoviskij and Czerny, 2002). Moreover, Syer et al. (1991) showed that a star on a highly eccentric orbit around a SMBH could lose enough energy and momentum on each passage through the neighboring accretion disk to bring the star into corotation with the disk. If compact objects are brought into corotation with the disk, they could gain a substantial mass through accretion and burst repeatedly as novae (Shields, 1996).

An interesting example of what one can learn from star-disk collisions comes from Dai et al. (2010). When a star impacts an accretion disk and travels through it, the exit of the star can leave a large magnitude and short duration X-ray flare (this actually explains an X-ray flare at the GC, see Baganoff et al., 2001; Nayakshin et al., 2004). If a star is on a bound orbit around a SMBH, it will impact the neighboring accretion disk multiple times, each one leading to a X-ray flare. Therefore, the periodicity of X-ray flares should give insight to the characteristics of the stars orbit and if the orbit is relativistic, then we can estimate properties of the central SMBH such as mass and spin.

On a seemingly unrelated note, the reported observations in Krabbe et al. (1991), Najarro et al. (1994), Buchholz et al. (2009), Do et al. (2009), and Bartko et al. (2010) indicate a relative paucity of RG stars with the ages of approximately 10^8 - 10^9 years in the GC as well as a high concentration of hot blue stars. The discovery of these “missing” RGs poses a theoretical problem. We would have expected the GC to have formed a segregated cusp of late-type stars due to the central gravitational potential of the SMBH.

A number of authors have addressed the problem of these missing RGs in our GC. Proposed explanations include star-star collisions due to the high density of stars within the central parsec of the GC (Genzel et al., 1996; Davies et al., 1998; Bailey and Davies, 1999; Alexander, 1999; Dale et al., 2009), MBH binaries scouring out a core in the GC via three-body slingshots (Baumgardt et al., 2006; Portegies Zwart

et al., 2006; Matsubayashi et al., 2007; Löckmann and Baumgardt, 2008; Gualandris and Merritt, 2012), and infalling star clusters (Kim and Morris, 2003; Ernst et al., 2009; Antonini et al., 2012). However, it has recently been suggested that star-disk collisions, in particular, play a prominent role in the shape and appearance of the NSC in the GC (Ghez et al., 2005; Genzel and Karas, 2007; Gillessen et al., 2009) and this indication hints at a promising explanation for the missing RGs.

Such an explanation for the missing RGs involving star-disk collisions has been put forward by Ghez et al. (2003); Bartko et al. (2011); Amaro-Seoane (2013). It starts with evidence for a stellar disk surrounding the SMBH extending out to approximately 0.4 pc (Tanner et al., 2006; Paumard et al., 2006; Lu et al., 2009; Bartko et al., 2011). The existence of such a disk suggests the fragmentation of an accretion disk around the central SMBH which leads to star formation in the disk (Levin and Beloborodov, 2003; Alexander et al., 2008). It is possible that RGs in the NSC collided with dense clumps in the fragmenting disk (a discussion of the probability of such encounters can be found in Amaro-Seoane, 2013). Because they have compact cores surrounded by tenuous outer layers, RGs are particularly vulnerable to collisions, which can lead to large amounts of mass loss from the impacting star. If the RGs collided with the fragmenting accretion disk, it is plausible that they could have been rendered invisible from observation or even completely disrupted.

In our work we set out to test the hypothesis that the missing RGs are a result of impacts with a fragmenting disk via high resolution hydrodynamic simulations. We will almost exclusively focus on bounding the amount of mass our RG loses during a collision with an accretion disk with respect to orbital velocity and disk density. We should note, however, that this investigation is preceded by another numerical work which considered a similar scenario. Armitage et al. (1996) used smoothed particle hydrodynamic simulations to study the possibility that RGs could be an indirect source of fuel for the SMBH in active galactic nuclei. As suggested, the low binding

energy of the stellar envelope for a RG will make the envelope susceptible to stripping during a collision and the excess mass stripped would then be deposited into the disk. This, in turn, would continually replenish the accretion disk with material to feed the SMBH. They showed that for RGs with $R_* \sim 150R_\odot$, significant mass deposition would ensue, i.e., the RG star can in the most destructive cases be completely stripped of its outer envelope.

Our work improves on that of [Armitage et al. \(1996\)](#) by implementing higher resolution grid based hydrodynamic simulations allowing for a more accurate analysis of the mass stripping. Furthermore, we will focus on the case of RGs with radius $R_* = 10R_\odot$. Such RGs with that radii are more common in NSCs like our own. However, a smaller stellar radius implies higher binding energy of the envelope, which means that RGs with $R_* = 10R_\odot$ will be harder to strip and disrupt than the RGs considered by [Armitage et al. \(1996\)](#).

This thesis is organized as follows: in [§2](#) we give a detailed overview of the numerical methods used to study RGs colliding with an accretion disk as well as a description of different initial conditions for the star and disk configuration. In [§3](#), we present the results of our study, primarily focusing on the amount of mass the RG loses during impact. In [§4](#), we discuss the implications of our results and the role of any physical processes that we do not model. Finally, in [§5](#) we conclude and discuss future avenues of research.

Chapter II

NUMERICAL SETUP

To model the collision between a star and accretion disk, we tailor a version of the hydrodynamics code VH-1 developed by [Cheng and Evans \(2013\)](#). VH-1 is a grid based parallel hydrodynamics code that uses finite difference approach to solve the Euler equations based on a Lagrange-Remap version of the Piece-wise Parabolic Method (for more detail, see [Blondin et al., 2012](#); [Colella and Woodward, 1984](#)). The Euler equations are given in the form of an ideal inviscid compressible gas flow with fixed adiabatic index γ and with gravitational acceleration terms¹. The [Cheng and Evans](#) version of the code uses a spectral collocation technique for the self-gravity (i.e., one solves Poisson’s equation using a discrete sine transform in three dimensions).

The code has been tested against several standard problems, see [Cheng and Evans](#) and references therein. Moreover, the code has been used extensively by [Cheng and Evans](#) to model the tidal disruptions of stars by black holes. This version of the code is also advantageous for our project because of the code’s shock capturing scheme. This is beneficial because we expect a strong bow shock to form at the front of the star after impact.

The coordinate system in the hydrodynamics code is taken to be Cartesian and the computational domain is a cube centered on the RG. In our code units, one length along an axis of our domain corresponds to 1 RG radii. Each side of the

¹The Euler equation for conservation of momentum is

$$\partial_t (\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u}) + \nabla p = \rho \mathbf{a} \quad (1)$$

where ρ is the mass density, p is the gas pressure, and \mathbf{u} is the fluid velocity. By acceleration terms we mean the \mathbf{a} that appears on the right hand side. It represents a local acceleration such as gravity. There is the similar equation for energy conservation with \mathbf{a} appearing as well.

cube has length 4 in our code units and the cube is partitioned along each Cartesian axis according to our choice of resolution with 6 ghost zones extending from each boundary surface of the cube. We initially place the RG at the center of the domain and then change to a reference frame in which the velocity of the center of mass is zero so that the RG remains in the center of the domain throughout the simulation. All boundary surfaces use a zero-gradient outflow boundary condition (i.e., fluid may freely flow out) except for one boundary surface through which we send an inflow of matter representing a local region of the accretion disk. With this setup up, we are essentially placing the RG in a “wind tunnel”.

2.1 *Properties of the RG star*

Everything in our study is local and focused on the RG (i.e., we do not consider effects that may occur beyond $2R_*$). We assume the RG is a polytrope which obeys the generic polytropic relation between pressure and density $P = K\rho^\Gamma$ where $\Gamma = 1 + 1/n$ is the adiabatic index and n is the polytropic index. From this assumption the initial density profile of the RG is constructed by numerically solving Lane-Emden’s equation² for different polytropic indices. We study two polytropic indices $n = 3/2$ and $n = 3$ corresponding to adiabatic index $\Gamma = 5/3$ and $\Gamma = 4/3$, respectively. The physical difference between the two adiabatic indices is shown in Figure 2.1. From the curves $\Sigma_\Gamma(r)$ in Figure 2.1, we can observe that a star with adiabatic index $\Gamma = 4/3$ has a more compact core relative to a star with $\Gamma = 5/3$.

In order to appropriately model the stars from the GC, we choose to study a RG

²Lane-Emden’s equation describes a polytrope, i.e., a Newtonian self-gravitating gaseous sphere. The equation takes the following dimensionless form

$$\frac{1}{\xi^2} \frac{d}{d\xi} \left(\xi^2 \frac{d\theta}{d\xi} \right) + \theta^n = 0 \quad (2)$$

where θ and ξ are related to the density and radius (respectively) by $\rho = \rho_c \theta^n$ and $r = \alpha \xi$. Here ρ_c is the central density of the polytrope. For most choices of rational n , the equation does not admit an analytic solution and must be solved numerically.

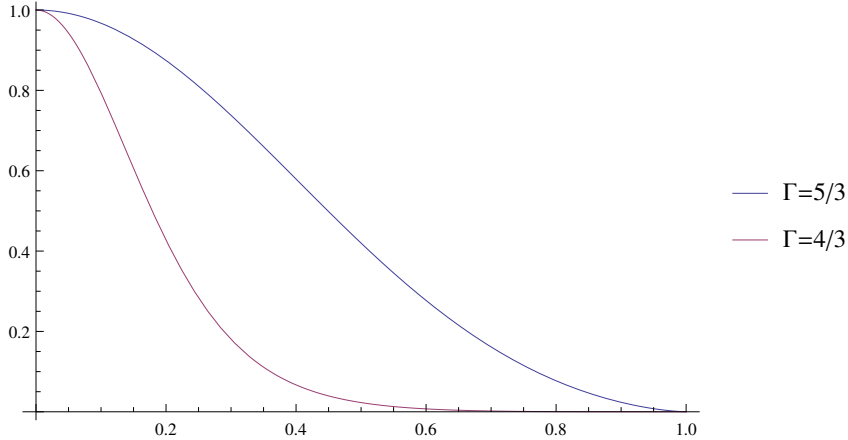


Figure 1: A plot of the initial density $\rho(r)$ of two polytropes of radius 1. The Γ in the legend indicates the adiabatic index of each star.

with an initial radius of $R_* = 10R_\odot$ and mass of $M_* = 1M_\odot$. From this we calculate the rest of the RG parameters such as density and pressure using the relationships given in the chapter IV of classic text on stellar structure [Chandrasekhar \(1967\)](#).

2.2 Background atmosphere

The grid based hydrodynamics solver requires that the RG sit in some low-density ambient atmosphere. We wish to choose the density and pressure of the background atmosphere, ρ_a and p_a (respectively), so that the background does not affect the evolution of the star. We accomplish this by initially placing the RG in a background atmosphere with prescribed density $\rho_a = 10^{-15}\rho_c$ where ρ_c is the central density of the RG ($\rho_c = 1$ in our simulations). Regardless of the adiabatic index Γ we use for the polytrope, we set the adiabatic index of the background atmosphere to be $\gamma = 5/3$. To set the pressure of the atmosphere, we move on the assumption that the value for the initial atmospheric sound speed c_a can be taken to be equal to the virial velocity at $r = 2R_*$,

$$c_a^2 = M_*/2R_* \quad (3)$$

The atmospheric pressure is then set equal to

$$p_a = c_a^2 \cdot \rho_a / \gamma \quad (4)$$

From here we evolve the domain by sending in the fluid that represents the accretion disk from one of the boundaries.

2.3 Orbital Velocities

We calculate the orbital velocity of the star by assuming that the orbit is Keplerian, i.e.,

$$v_* \simeq \sqrt{GM_{\text{en}}/r} \quad (5)$$

where M_{en} is the total mass of enclosed by the orbit, that is $M_{\text{en}} \simeq M_{\bullet} + M_{\text{st}}$ where M_{\bullet} is the mass of the central SMBH and M_{st} is the total mass of the stellar population within the given orbital radius. In our code we are considering $M_{\bullet} = 4 \times 10^6 M_{\odot}$ in order to represent the radio source Sgr A*. We choose to study three velocities $v = 300, 600, 900 \text{ km s}^{-1}$ which correspond to $r = 0.191, 0.048, 0.021 \text{ pc}$ away from the central SMBH, respectively. Along with those three velocities, we also consider RGs on orbits with $r = 1.0 \text{ pc}$, corresponding to approximately $v_* = 150 \text{ km s}^{-1}$. To support this assumption, [Trippe et al. \(2008\)](#) provides map three dimensional velocities for hundreds of RGs in the GC. They measure velocities of approximately a few 100 km s^{-1} for most RGs which justifies our approximation and choices.

2.4 Properties of the Accretion Disk

Initially we chose our accretion disk model based off the results of [Shakura and Sunyaev \(1973\)](#). In particular, the column density, thickness, and temperature of the disk are calculated under the assumption that the disk's pressure is determined by the gas pressure, the sound speed is given by $v_s = \sqrt{k_B T / m_p}$, and the opacity of the disk is determined by electron scattering. With this assumption the column density

of the disk Σ at a given radius away from the central black hole is

$$\Sigma = (1.7 \times 10^5) \alpha^{-4/5} \left(\frac{\dot{M}}{\dot{M}_{\text{cr}}} \right)^{3/5} \left(\frac{M}{M_{\odot}} \right)^{1/5} \left(\frac{R}{3R_g} \right)^{-3/5} \times \left(1 - \left(\frac{R}{3R_g} \right)^{-1/2} \right)^{3/5} \quad (6)$$

where α is a parameter characterizing the efficiency of angular momentum transport in the disk (taken to be 0.1 for our calculation), \dot{M}_{cr} is the accretion rate onto the black hole such that the total release of energy in the disk is equal to the Eddington critical luminosity³, and $R_g = 2GM/c^2$ is the Schwarzschild radius. Similarly, the half-thickness of the disk is given by

$$Z = (1.2 \times 10^4) \alpha^{-1/10} \left(\frac{\dot{M}}{\dot{M}_{\text{cr}}} \right)^{1/5} \left(\frac{M}{M_{\odot}} \right)^{9/10} \left(\frac{R}{3R_g} \right)^{21/20} \times \left(1 - \left(\frac{R}{3R_g} \right)^{-1/2} \right)^{1/5} \quad (8)$$

Our first few simulations used this model to calculate the density and pressure of the inflowing material. For example, an orbital velocity of $v_* = 300 \text{ km s}^{-1}$, will have a corresponding radial distance away from the black hole such that the disk column density and thickness (or height) at that radius is $\Sigma = 3138 \text{ g cm}^{-2}$ and $2Z = 1.4 \times 10^{15} \text{ cm}$, respectively. From this the density is $\rho = \Sigma/2Z_0$. Running a simulation with 128^3 grid resolution using $v_* = 300 \text{ km s}^{-1}$ yields a very low value for the total change in mass (on the order of 0.0001% in $100 t_{\text{dyn}}$, see §2.5 for the definition of t_{dyn}). Thus if we use this model, we would need to go to unreasonably high orbital velocities to find any notable change in the total mass.

Thus, we proceed to construct a model of the fragmenting accretion disk motivated [Amaro-Seoane \(2013\)](#) and correspondingly we suppose that the RG will be colliding

³For a black hole of mass M , the \dot{M}_{cr} is given by

$$\dot{M}_{\text{cr}} = (3 \times 10^{-8}) \left(\frac{0.06}{\eta} \right) \left(\frac{M}{M_{\odot}} \right) \frac{M_{\odot}}{\text{year}} \quad (7)$$

where η is the efficiency of gravitational release, approximately 0.06 for a Schwarzschild black hole.

with a fragmenting portion of the accretion disk. We will say that the RG is colliding with a *clump* in the accretion disk. Since the clump density will be much higher than that of the surrounding disk, we can assume that density of the inflowing material is much higher for $v_* = 300 \text{ km s}^{-1}$ than what would be calculated from the disk model in [Shakura and Sunyaev \(1973\)](#).

We approximate the clump in the disk as being spherically symmetric and we take the radius of the clump R_c to be

$$R_c = \min \{ \sqrt{M_c / \pi \Sigma_c}, 2Z \} \quad (9)$$

where M_c is the mass of the clump, Σ_c is the column density of the clump, and Z is the half-thickness of the disk given by equation 8. As before, the radius used to calculate Z is given by the orbital velocity of the star for a particular simulation. In our simulations we will be fixing a value for the column density of the clump ($\Sigma_c = 10^7$ or 10^8 g cm^{-2}) and varying the orbital velocities (namely, those mentioned in §2.3). Moreover, following the assumptions in [Amaro-Seoane \(2013\)](#), we choose a clump mass of $M_c = 10^2 M_\odot$ to calculate R_c . We find that for every combination of Σ_c and v_* , we find $R_c = \sqrt{M_c / \pi \Sigma_c}$. Hence, we take this as the definition of R_c . This is reasonable since in the clump formation, the gas will have contracted in some way, forcing the radius to be smaller than the height of the disk.

Now that we know R_c , the actual density of the clump used for our simulations will be given by

$$\rho_c = \frac{3}{4} \pi^{1/3} \Sigma_c^{3/2} M_c^{-1/3} \quad (10)$$

and, similarly, the pressure of the clump will be given by

$$p_c = \frac{k_B \rho_c T}{m_p} = \frac{2G \rho_c M_c}{3R_c} \quad (11)$$

Our primary simulations (or runs) of interest with the corresponding values of Σ_c , R_c , ρ_c , and p_c are given in Table 2.5 along with a few other parameters that characterize a particular run.

2.5 Characteristic timescales

For the purposes of our code, we define the *dynamical time*,

$$t_{\text{dyn}} = \frac{R_*}{\sqrt{GM_*/R_*}} \quad (12)$$

which is simply the time it takes for a sound wave to travel through the RG. This is the time unit we use in our code. All time scales from now on will be given in units of t_{dyn} .

Further, we calculate a clump crossing time $t_c = R_c/v_*$ to obtain a measure on how many times the RG travels through the entire clump. From the functional dependence of R_c on Σ_c , we can see that as we increase Σ_c , R_c will decrease. This means that the t_c will become smaller as we try to impact our RG star with denser clumps. The number of times our RG passes through the clump in $100 t_{\text{dyn}}$ for various values of Σ_c and v_* is given in Table 3.2.

We also calculate the number of times we expect the RG to collide with accretion disk in its lifetime. First we recall that orbital period of a RG with orbital radius of 0.5 pcs will be given by

$$t = 2\pi \sqrt{\frac{r_*^3}{GM_{\text{en}}}} \simeq (3.6 \times 10^6) t_{\text{dyn}} \quad (13)$$

The lifetime of a star of mass $1M_\odot$ is approximately a few Gyrs. The RG phase itself for $1M_\odot$ is less than 1 Gyr. Let us take the lifetime of our RG to be 500 Myr. Then, noting that the star will cross the disk twice every time it completes an orbit, we find that the star will impact the disk approximately 175,000 times in its lifetime. If the disk is fragmenting, the number of times the RG impacts a clump will be some small fraction of 175,000. Of course this is a crude approximation since every time the star impacts the disk it will lose orbital energy bring it to the SMBH which will not only increase the star velocity but also make it more susceptible to star-star collisions and tidal disruption.

Table 1: The parameter range explored in our main simulations of interest. The adiabatic index for the RG in all rows below is $\Gamma = 5/3$. Column (1) gives our label to a particular simulation. Column (2) gives the grid resolution used for that particular run. Column (3) is the velocity of the star. Column (4) is the column density of the clump in the accretion disk. Column (5) is the radius of the disk clump. Column (6) is the mach number (i.e., $\mathcal{M} = c_*/c_{\text{atm}}$). Column (9) is the initial impacted mass. Column (10) is the momentum transferred at impact. Column (11) is the energy transferred at impact.

Run	Resolution	v_* km s ⁻¹	Σ_c g cm ⁻²	R_c cm	ρ_d g cm ⁻³	p_d erg cm ⁻³	\mathcal{M}	M_i M _⊙	p_i g cm s ⁻¹	E_i erg
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Run1	128 ³	300	10 ⁷	7.9 × 10 ¹³	9.4 × 10 ⁻⁸	10 ⁷	2.2	7.6 × 10 ⁻⁵	4.5 × 10 ³⁶	6.8 × 10 ⁴³
Run2	128 ³	600	10 ⁷	7.9 × 10 ¹³	9.4 × 10 ⁻⁸	10 ⁷	4.4	7.6 × 10 ⁻⁵	9.1 × 10 ³⁶	2.7 × 10 ⁴⁴
Run3	128 ³	900	10 ⁷	7.9 × 10 ¹³	9.4 × 10 ⁻⁸	10 ⁷	6.6	7.6 × 10 ⁻⁵	1.3 × 10 ³⁷	6.1 × 10 ⁴⁴
Run4	128 ³	300	10 ⁸	2.5 × 10 ¹³	2.9 × 10 ⁻⁶	10 ⁹	1.2	7.6 × 10 ⁻⁴	4.5 × 10 ³⁷	6.8 × 10 ⁴⁴
Run5	128 ³	600	10 ⁸	2.5 × 10 ¹³	2.9 × 10 ⁻⁶	10 ⁹	2.4	7.6 × 10 ⁻⁴	9.1 × 10 ³⁷	2.7 × 10 ⁴⁵
Run6	128 ³	900	10 ⁸	2.5 × 10 ¹³	2.9 × 10 ⁻⁶	10 ⁹	3.7	7.6 × 10 ⁻⁴	1.3 × 10 ³⁸	6.1 × 10 ⁴⁵

Chapter III

RESULTS

3.1 *Massloss mechanism*

Before presenting the results of all our simulations, we briefly summarize the two primary contributions to the massloss as described in [Armitage et al. \(1996\)](#). The content of [Armitage et al. \(1996\)](#) is based on a similar theory developed in [Wheeler et al. \(1975\)](#) which considers the effect of a star being impacted by a supernova blast wave as a result of being a companion star in a binary system. This theory is similar but there are some deviations because of the relative difference in the duration and velocity of an impact for a RG colliding with an accretion disk and a RG colliding with a supernova blast wave.

With this in mind, we expect that most of the massloss due to the collision will occur via momentum transfer. That is, direct momentum transfer strips matter from the outside of the star down to some fraction of the stellar radius. This critical radius is the radius where the momentum transferred to a cylindrical shell is just sufficient to accelerate it to the stellar escape velocity at that radius. The critical radius which outside of all the mass is expected to be stripped can be found by solving for the roots of the following equation,

$$\Sigma_*(r)v_{\text{es}}(r) - v_*\Sigma_c = 0 \quad (14)$$

where $v_{\text{es}}(r)$ is the escape velocity of the RG at a radius r and $\Sigma_*(r)$ is the column density of the RG at the radius $r \leq R_*$.

There is also an ablation component to the massloss which can be described as follows. When the star impacts the disk, there is a shock that is driven into the star as a consequence of the impact. This shock will heat the material on the surface of

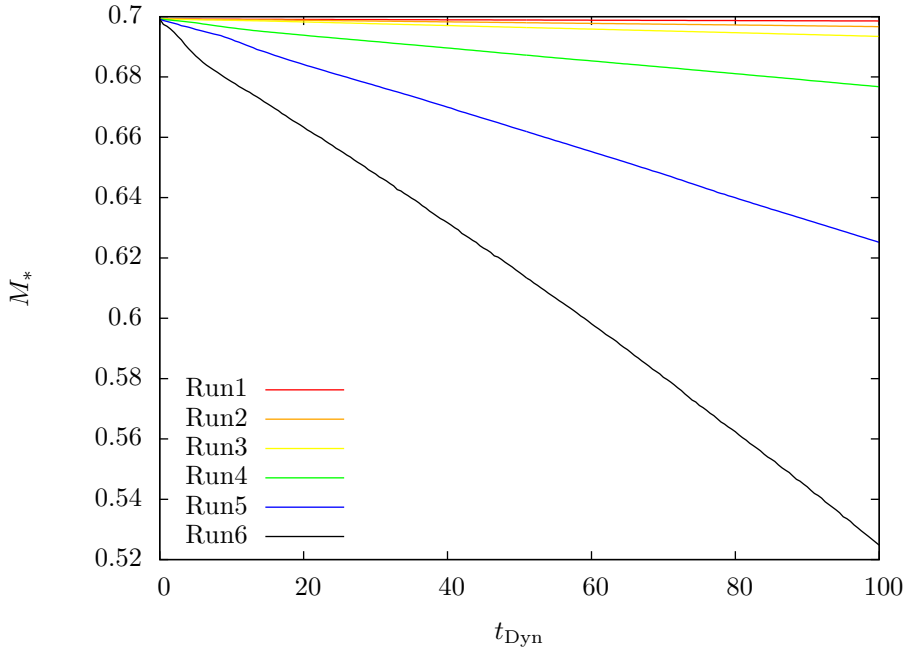


Figure 2: The massloss of the RG as a function of dynamical time for each of the main runs under study. All the runs are at 128^3 resolution. Note that from comparison with Table 2.5, all of these runs are of supersonic.

the star and once the star exits the disk, the thermal energy will transfer to kinetic energy and the heated material will escape the stellar surface. The material that boils off the surface of the star is the ablation component of the massloss. However, we do not expect this ablation component to contribute much to the total massloss for a star-disk collision. This is because we expect the shock to be much stronger for the case of a supernova blast wave unless the velocity of the star colliding with an accretion disk is sufficiently high.

3.2 Results for runs with $\Gamma = 5/3$

Our main runs of interest are given in Table 2.5. We find that the massloss increases as you proceed from Run1 to Run6. Figure 3.1 shows the massloss of the RG as a function of dynamical time t_{dyn} for the simulation Run1-6 in Table 2.5. We can observe from Figure 3.1 that the massloss becomes significant for the impacts with

Table 2: Massloss calculation for the RG star after $100t_{\text{dyn}}$. *Crossings* indicates the number of times that RG has passed through the clump in $100t_{\text{dyn}}$.

Run	Resolution	t_{dyn}	Crossings	M_{loss} %
Run1	128^3	100	2	0.09
Run2	128^3	100	4	0.36
Run3	128^3	100	6	0.82
Run4	128^3	100	6	3.19
Run5	128^3	100	12	10.53
Run6	128^3	100	20	24.81

$\Sigma_c = 10^8 \text{ g cm}^{-2}$. In particular, we find that the star loses approximately 25% of its mass in Run6 after $100 t_{\text{dyn}}$. Since the initial mass of the RG is $1M_{\odot}$, the total mass stripped is approximately $0.25M_{\odot}$. The massloss percentage for all the runs is given in Table 3.2.

To provide contrast to Figure 3.1, we present Figure 3.2 which gives the central density as a function of t_{dyn} . We can see from the solid black line for Run6, that the star “rings” once it impacts the accretion disk. Thus we can conclude that the central density is initially perturbed from its equilibrium value and then executes damped oscillations about this value until arriving at equilibrium again. Notice that this return to equilibrium happens even though the star doesn’t exit the disk, unless the impact is sufficiently disruptive.

To explore a wider parameter space, we also conduct a run with velocity corresponding to the RG orbiting at 1 pc. In particular, we look at clump densities and pressures which result from $\Sigma_c = 10^8 \text{ g cm}^{-2}$ (as in Run4-6) but the collision occurs at an orbital velocity of roughly 150 km s^{-1} . Figure 3.2 shows the massloss as a function of dynamical time over a period of one disk crossing (approximately $34 t_{\text{dyn}}$) for this setup. We find that after one disk crossing the RG has lost approximately 0.5% of its total mass. Though this is small, it corresponds to only one disk crossing. After several impacts we expect that the massloss will accumulate and hence, even at 1.0

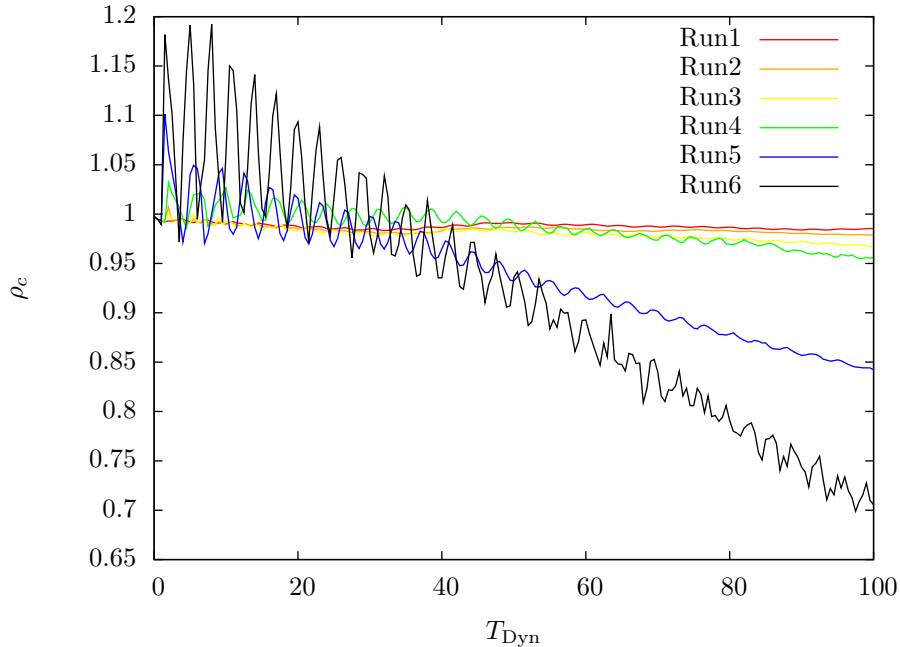


Figure 3: A plot of the central density as a function of dynamical time for each of the main runs under study.

pc a RG of $10R_{\odot}$ can experience not negligible envelope stripping.

The runs presented thus far have simulated a RG continually traveling through the disk and never exiting. In reality, the star would impact the disk repeatedly throughout its lifetime, each impact experiencing a transit time given by t_c in Table 3.2. Thus, we conduct a run with periodic impact to demonstrate the effect of exiting and reentering the disk. The massloss as a function of t_{dyn} for a repeated impact version of Run6 at 1 pc is shown in Figure 3.2. We produce this periodic impact by setting our boundary conditions to vary periodically based on the clump crossing time t_c . When the star exits the clump, we wait $2t_c$ before sending in the clump material again. This is to allow the star to settle into an equilibrium state before another impact. It is of interest to note that Figure 3.2 indicates the star actually regains some of its mass after it exits the disk.

In regards to the periodic impacts, it is shown in Armitage et al. (1996) that the

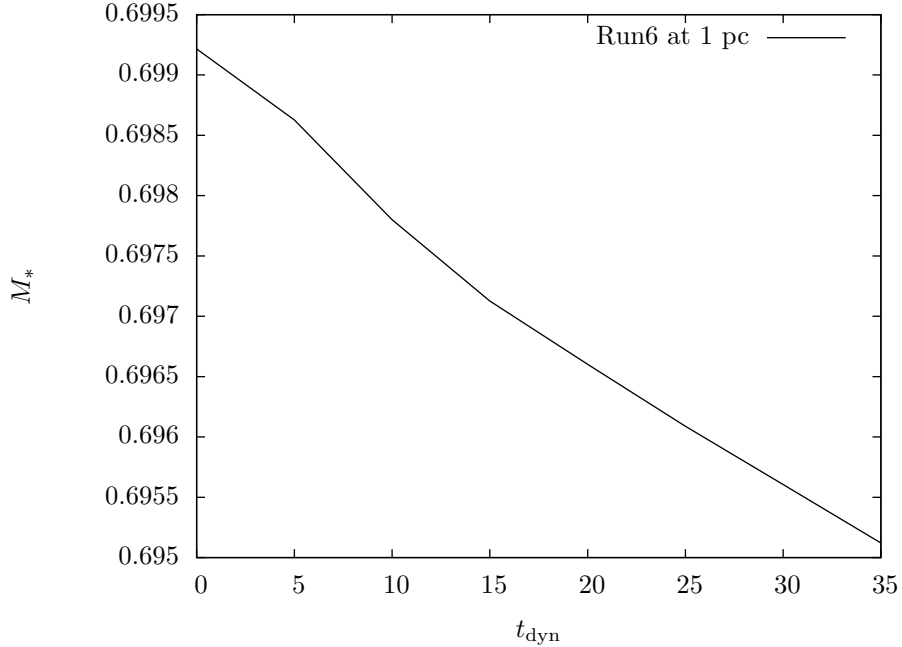


Figure 4: A plot of the massloss as a function of dynamical time for a RG which orbiting at a distance of 1 pc away from the SMBH. In the above run the column density of the clump is $\Sigma_c = 10^8 \text{ g cm}^{-2}$, just as it is in Runs 4-6 given in Table 2.5

radius of the RG (where their $R_* = 150 R_\odot$) will increase significantly after impact (their calculations show that the radius is increased approximately 30%). This allows for more efficient stripping when the star impacts the disk again since the binding energy of the envelope of the RG will have decreased. See §4.1.1 for more details on this.

To conclude this section, we provide a detailed visualization for Run5 as shown in Figure 3.3. The Figure shows a two dimensional plot (in the $z = 0$ plane) of the temperature throughout the computational domain. This type of visualization aids in revealing hydrodynamical instabilities that may appear on the surface of the star during impact as well as the strong shock that forms in front of the star as a result of supersonic impact.

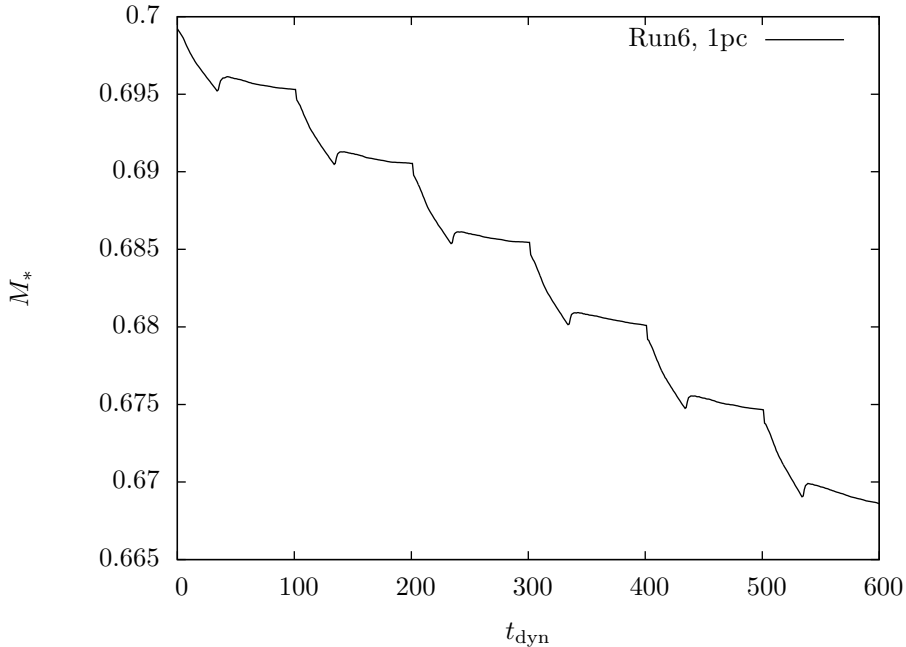


Figure 5: The Figure on the left shows the massloss as a function of dynamical time for Run6 at 1 pc that includes repeated impacts with the disk. At $t_{\text{dyn}} = 0$ the star enters the disk and exits the disk at $t_{\text{dyn}} = 34$. After the clump exits the disk, it moves through vacuum until $2t_c$ where it re-enters the disk. This is illustrate by the stair-like curve shown.

3.3 Main Runs for $\Gamma = 4/3$

In addition to studying RG stars with polytropic index $\Gamma = 5/3$, we also explore collision using a RG that has $\Gamma = 4/3$. The primary purpose of looking at a different polytropic index is to study the effect different polytropic indices have on the envelope stripping. We run two simulations with $\Gamma = 4/3$ and compare them to the results obtained in the case $\Gamma = 5/3$. In order to have numerical accuracy for the case of $\Gamma = 4/3$, we must increase the resolution of our simulations to values greater than 256^3 . As a consequence, the simulations for $\Gamma = 4/3$ become more computationally expensive.

The first of these two simulations is the same as Run1 in Table 2.5 expect with a grid resolution of 300^3 (and $\Gamma = 4/3$). We choose this weaker impact to ensure

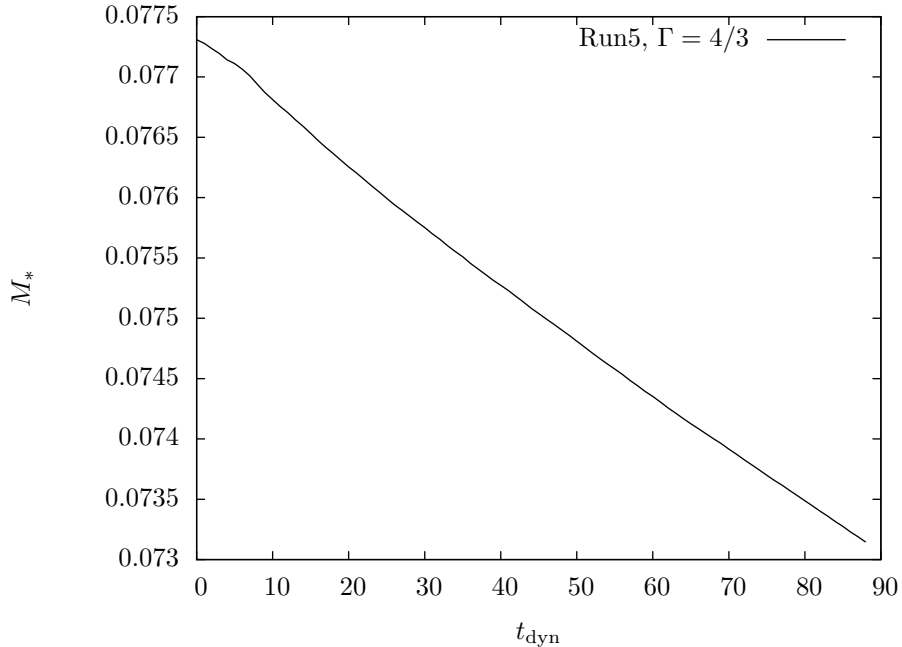


Figure 6: The Figure on the right shows the massloss as a function of dynamical time for a RG with polytropic index $\Gamma = 4/3$. The relevant parameters are $\Sigma_c = 10^8 \text{ g cm}^{-2}$ and $v_* = 600 \text{ km s}^{-1}$, so the sister run is Run5 from Table 2.5 and Figure 3.1.

that our RG is stable after a change in polytropic index. After $100 t_{\text{dyn}}$ we find the massloss for this run to be approximately 0.06%. This is reasonable since this is the weakest impact we are considering.

The second set of parameters we consider is the same as Run5 in Table 2.5 expect with a grid resolution of 384^3 . The results of this run are shown in Figure 3.2. We find a massloss of approximately 5% after approximately $100t_{\text{dyn}}$. This is about half of what is found for the case of $\Gamma = 5/3$.

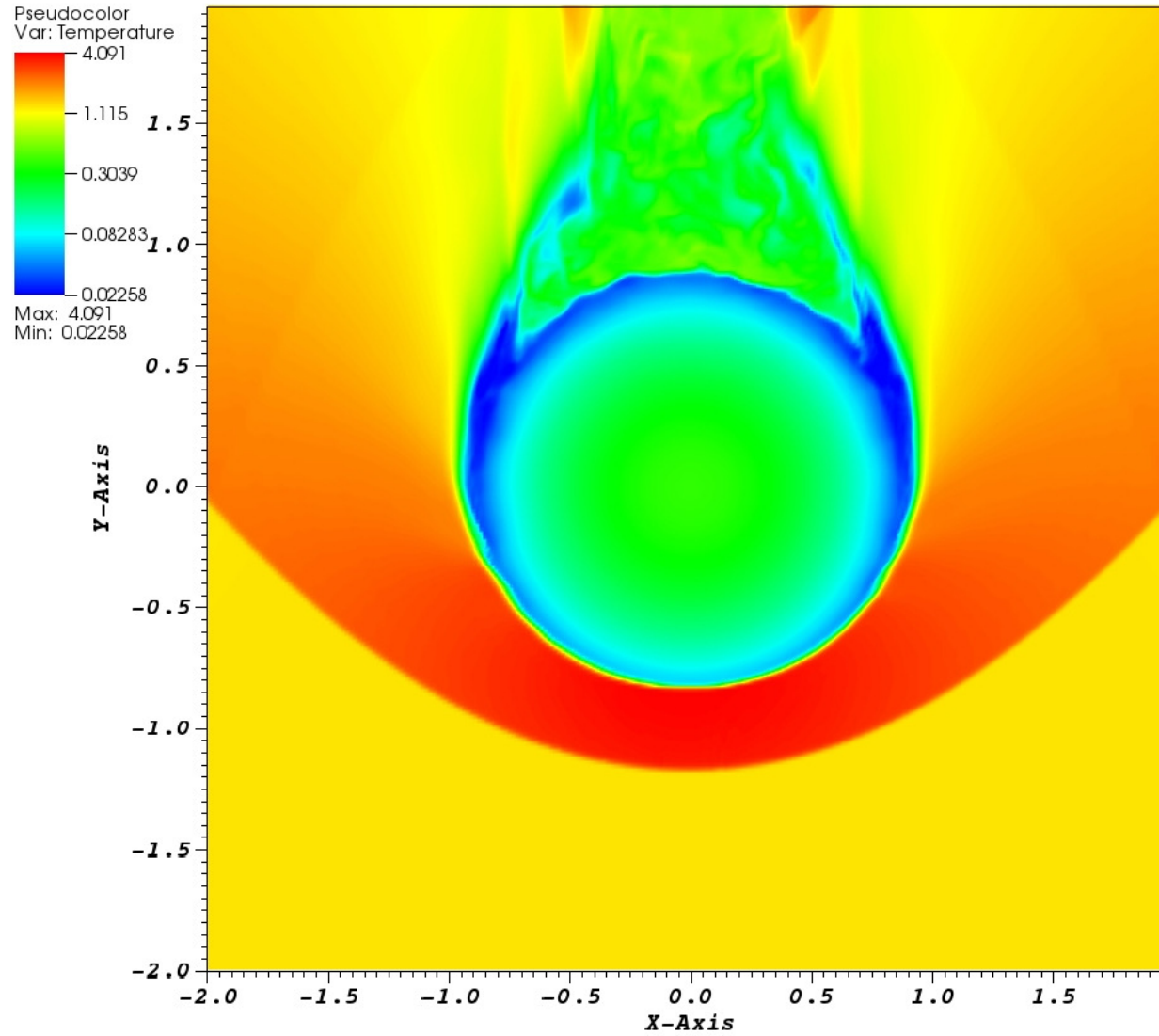


Figure 7: We take a slice through the $z = 0$ plane to show the temperature throughout the star. The resolution used here is 256^3 . The fluid that represents the clump in the accretion disk is moving in the positive y direction (upwards). One can observe the bow shock that is formed during passage.

Chapter IV

DISCUSSION

4.1 Luminosity after impact

Our results indicate that for a RG star of radius $R_* = 10R_\odot$, significant massloss can ensue (e.g., Run6 in Table 3.2). However, the question of whether this amount of massloss can render the RG invisible is open. Certainly if the RG is completely disrupted by a collision (which we would expect for clump column densities of $\Sigma_c > 10^8 \text{ g cm}^{-2}$ and/or velocities with $v_* \gtrsim 900 \text{ km s}^{-1}$), then the possibility of detection is out of the question. If this is not then case, then one must measure the luminosity of the RG as a function of its mass via a numerical code such as MESA (Paxton et al., 2011).

There have been successful attempts to measure the luminosity after a star has lost a significant fraction of mass due to some stripping mechanism. Dray et al. (2006) discuss the evolution in temperature and luminosity due to stripping of intermediate mass stars ($3-8M_\odot$) via the tidal forces produced by SMBHs. Though these calculations are based on actual evolutionary models, they are not a good match to our simulations of $1M_\odot$ RGs. Thus, we do not attempt to obtain these details in our study.

4.1.1 The altered structure of the RG

Each time a collision occurs and mass is stripped from the RG, the stellar structure of the RG will be altered. This is natural to expect since a decrease in total mass will allow radiation pressure to increase the stars radius. In particular, the work of Armitage et al. (1996); MacLeod et al. (2013) suggests that this expectation is true, the radius of the RG will increase every time mass is stripped.

4.2 *The role of other physical processes*

On a different note, it is well known that accretion disks can harbor both large and small scale magnetic fields. Our simulations are purely hydrodynamical, we do not model any magnetic fields. Therefore, we should consider what role, if any, ambient magnetic fields in an accretion disk might play in a star-disk collision. The question perhaps most relevant to our study is whether magnetic fields in the disk help shield the star from mass stripping. We aim to shed some light on this question.

The role of magnetic fields has been investigated thoroughly in the similar scenario of shocks impacting overdense clouds of gas in the interstellar medium (or intergalactic medium) where one considers either the shock to be magnetized, the cloud to be magnetized, or both (Mac Low et al., 1994; Fragile et al., 2005; Dursi, 2007; Dursi and Pfrommer, 2008; Shin et al., 2008). In any scenario, one generally finds that the presence of magnetic fields tends to lessen the chance the cloud will be destroyed. For example, Fragile et al. (2005) used two-dimensional numerical simulations to investigate of the interactions between magnetized shocks and radiative clouds with different magnetic field strengths and orientations. They find that tension in magnetic field lines along the tend to suppress the growth of hydrodynamical instabilities while external (internal) fields work to compress (expand) the cloud, whether radiative cooling is present or not. This seems to suggest that the presence of magnetic fields will tend to protect the cloud from disruption. These findings seem to suggest that the inclusion of magnetic fields in modeling star-disk collisions will have a effect on the post-encounter stellar structure.

Another point of interest is the bow shock that forms in front of the star shortly after impact (see the temperature profile in Figure 3.3 for a visual of the shock). Though it is likely the shock is prevents the star from losing mass via momentum transfer, the shock will contribute to an extra ablation component of the massloss.

Chapter V

CONCLUSION

In summary, we have provided concrete evidence that a RG of radius $R_* = 10R_\odot$ and mass $M_* = 1M_\odot$ experiences significant mass stripping when impacting a dense clump of gas in a fragmenting accretion disk. In general our results can be summarized by the following bounds for the massloss found in our main simulations of interest ($\Gamma = 5/3$):

$$1\% \lesssim M_{\text{loss}} \lesssim 25\%$$

Though a 1 % decrease in mass may seem negligible, over the lifetime of the RG the loss may accumulate causing an alteration in the luminosity of the RG.

In this work we focused on getting a measure of the massloss for different disk densities, stellar orbital velocities, and polytropic indices. However, a more extensive study is of interest. Future work includes getting proper estimates on the contribution of different massloss components to the total massloss along with an analysis of hydrodynamical instabilities that appear on the surface of the star as it passes through the disk (e.g., Kelvin-Helmholtz instabilities). Moreover, consideration of the post-encounter stellar structure is of interest. This is due to considerations in [Armitage et al. \(1996\)](#) which show that a RG radius may increase by roughly 30 % after exiting the accretion disk. A similar and more detailed analysis on this aspect can be done as well. Finally, magnetic fields and radiation should be included to constrain the role these processes may play in the evolution of the RG during and after impact.

.1 Resolution Study

Here we examine the stability of the RG as a function of numerical resolution in order to demonstrate numerical convergence. Figure 8 and 9 captures this by giving the central density and massloss as a function of t_{dyn} for Run5 (see Table 2.5) and comparing several of these curves under an increase in resolution. From the data shown, we can observe the convergence of both the central density and massloss as resolution is increased. This indicates that our simulation are numerically accurate.

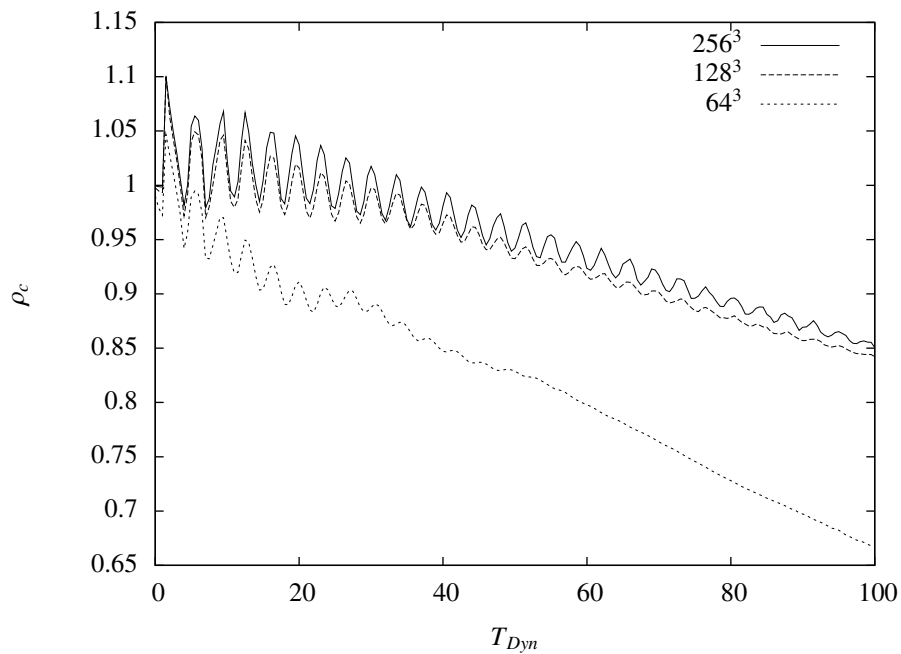


Figure 8: The convergence of the central density ρ_c upon increasing resolution for the run labeled Run5 in Table 2.5.

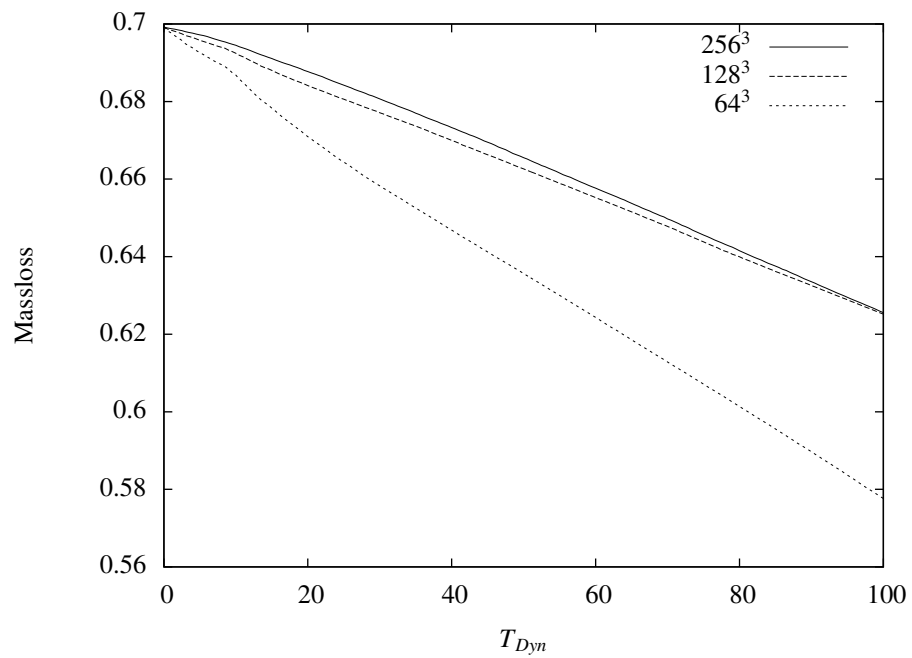


Figure 9: The convergence of the stellar mass as a function of dynamical time upon increasing resolution for the run labeled Run5 in Table 2.5.

.2 *Visualizations*

In this portion of the appendix, we provide two additional visualizations purely for fun.

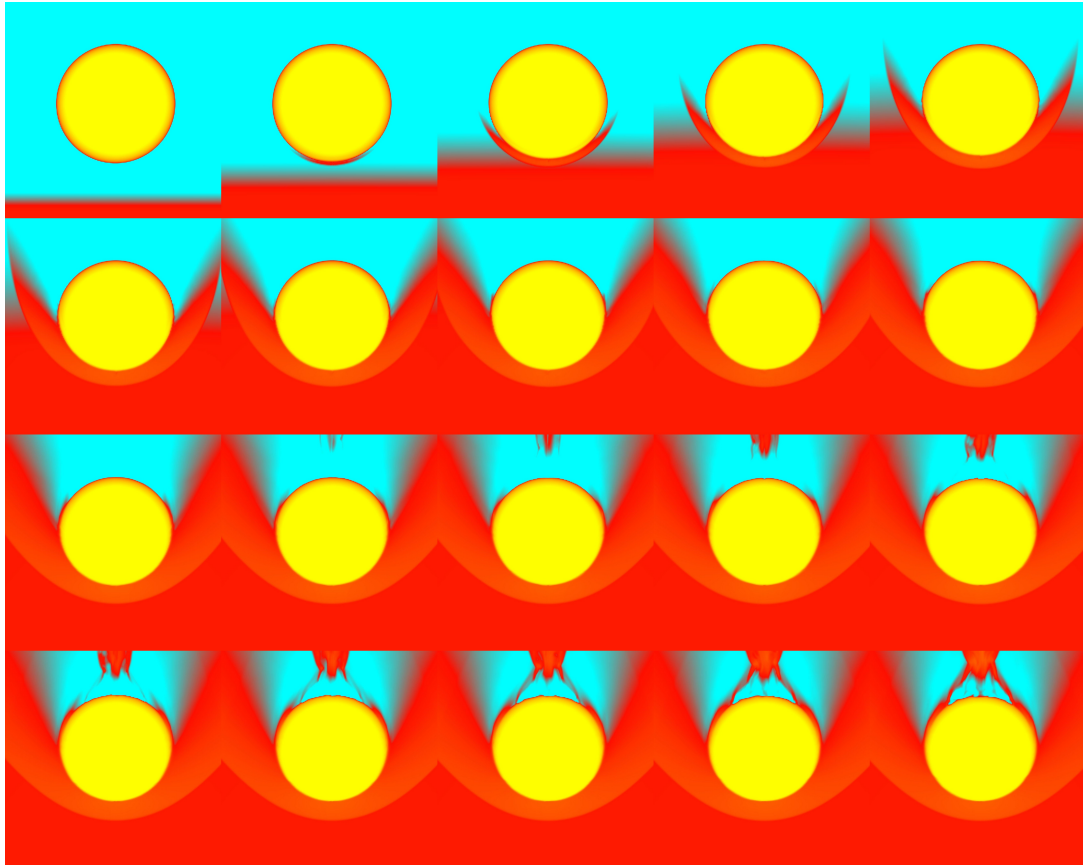


Figure 10: A sequence of images showing the RG impacting the accretion disk. The resolution used here is 128^3 . The images shown corresponds to that present in Figure 3.2. Both this Figure and Figure 11 are taken from the same simulation.

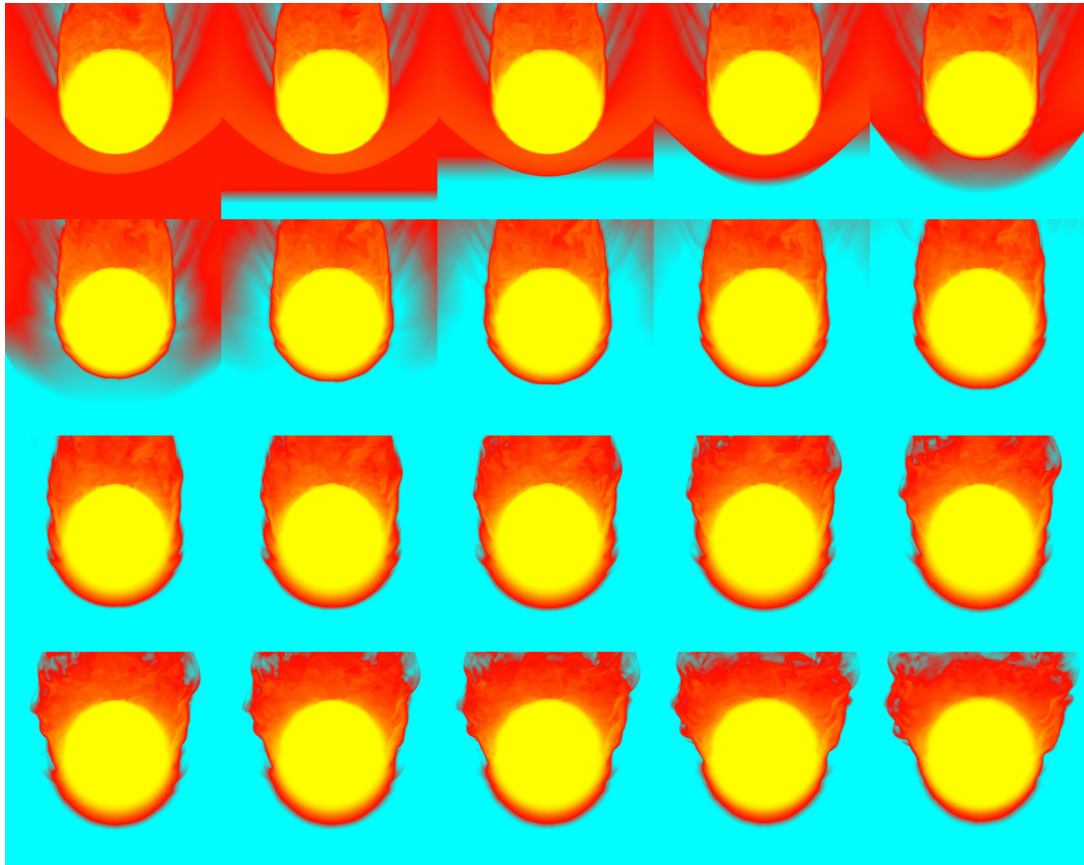


Figure 11: A sequence of images showing the RG exiting the accretion disk. The resolution used here is 128^3 . The images shown corresponds to that present in Figure 3.2. Both this Figure and Figure 11 are taken from the same simulation.

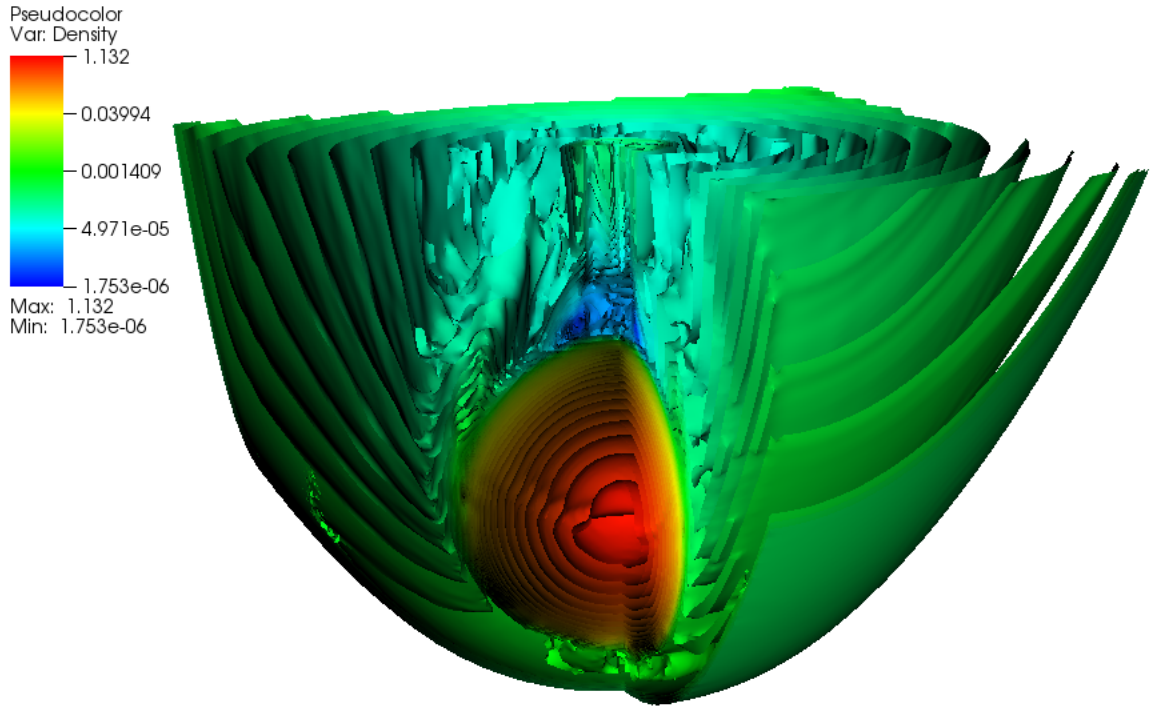


Figure 12: A 3-dimensional isosurface image of density just after the RG impacts the disk. The green surfaces on the outer edges represent the accretion disk. The RG is the orange/red region in the center. This particular simulation had a higher impact velocity ($v_* = 1200 \text{ km s}^{-1}$) and $\Sigma_c = 10^8 \text{ g cm}^{-2}$. Due to the high impact velocity the star gets completely disrupted during the impact.

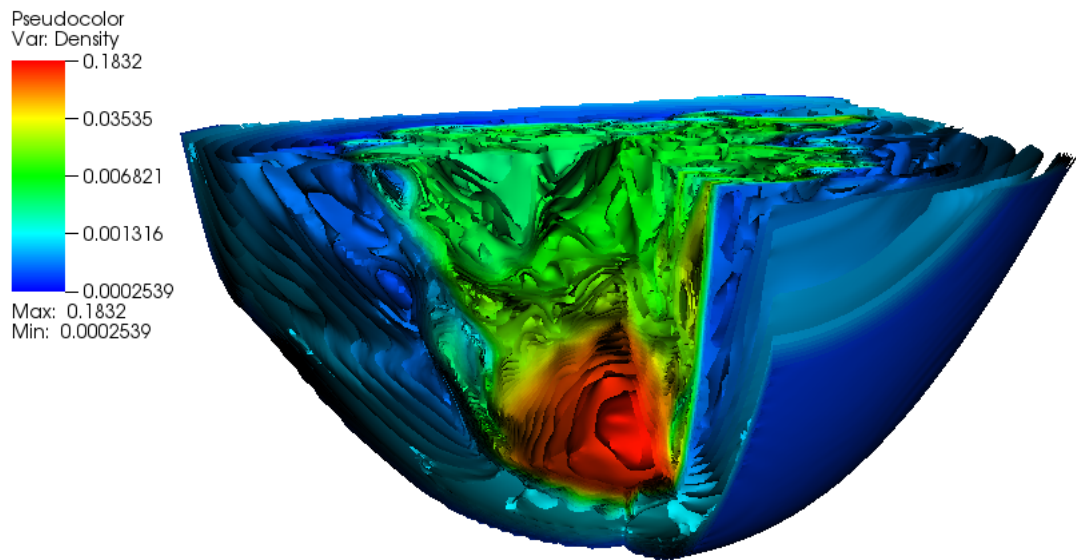


Figure 13: A 3-dimensional isosurface image of density just before the RG is disrupted. This is a few dynamical times after the impact shown in Figure 12.

Bibliography

- R. D. Alexander, P. J. Armitage, J. Cuadra, and M. C. Begelman. Self-Gravitating Fragmentation of Eccentric Accretion Disks. *The Astrophysical Journal*, 674:927–935, February 2008. doi: 10.1086/525519.
- T. Alexander. The Distribution of Stars near the Supermassive Black Hole in the Galactic Center. *The Astrophysical Journal*, 527:835–850, December 1999. doi: 10.1086/308129.
- X. Amaro-Seoane, P. & Chen. The fragmenting past of the disk at the Galactic Center : The culprit for the missing red giants. *ArXiv e-prints*, October 2013.
- F. Antonini, R. Capuzzo-Dolcetta, A. Mastrobuono-Battisti, and D. Merritt. Dissipationless Formation and Evolution of the Milky Way Nuclear Star Cluster. *The Astrophysical Journal*, 750:111, May 2012. doi: 10.1088/0004-637X/750/2/111.
- P. J. Armitage, W. H. Zurek, and M. B. Davies. Red Giant–Disk Encounters: Food for Quasars? *The Astrophysical Journal*, 470:237, October 1996. doi: 10.1086/177864.
- F. K. Baganoff, M. W. Bautz, W. N. Brandt, G. Chartas, E. D. Feigelson, G. P. Garmire, Y. Maeda, M. Morris, G. R. Ricker, L. K. Townsley, and F. Walter. Rapid X-ray flaring from the direction of the supermassive black hole at the Galactic Centre. *Nature*, 413:45–48, September 2001. doi: 10.1038/35092510.
- V. C. Bailey and M. B. Davies. Red giant collisions in the Galactic Centre. *Monthly Notices of the Royal Astronomical Society*, 308:257–270, September 1999. doi: 10.1046/j.1365-8711.1999.02740.x.
- H. Bartko, F. Martins, S. Trippe, T. K. Fritz, R. Genzel, T. Ott, F. Eisenhauer, S. Gillessen, T. Paumard, T. Alexander, K. Dodds-Eden, O. Gerhard, Y. Levin, L. Mascetti, S. Nayakshin, H. B. Perets, G. Perrin, O. Pfuhl, M. J. Reid, D. Rouan, M. Zilka, and A. Sternberg. An Extremely Top-Heavy Initial Mass Function in the Galactic Center Stellar Disks. *The Astrophysical Journal*, 708:834–840, January 2010. doi: 10.1088/0004-637X/708/1/834.
- H. Bartko, F. Martins, S. Trippe, T. K. Fritz, R. Genzel, T. Ott, F. Eisenhauer, S. Gillessen, T. Paumard, T. Alexander, K. Dodds-Eden, O. Gerhard, Y. Levin, L. Mascetti, S. Nayakshin, H. B. Perets, G. Perrin, O. Pfuhl, M. J. Reid, D. Rouan, M. Zilka, and A. Sternberg. Massive Young Stars in the Galactic Center. In M. R. Morris, Q. D. Wang, and F. Yuan, editors, *The Galactic Center: a Window to the Nuclear Environment of Disk Galaxies*, volume 439 of *Astronomical Society of the Pacific Conference Series*, page 100, May 2011.
- H. Baumgardt, A. Gualandris, and S. Portegies Zwart. Ejection of hypervelocity stars from the Galactic Centre by intermediate-mass black holes. *Monthly Notices of the*

- Royal Astronomical Society*, 372:174–182, October 2006. doi: 10.1111/j.1365-2966.2006.10818.x.
- J. Blondin, J. Hawley, G. Lindahl, and E. Lufkin. Virginia Hydrodynamics 1 (VH-1), 2012. <http://wonka.physics.ncsu.edu/pub/VH-1/>.
- R. M. Buchholz, R. Schödel, and A. Eckart. Composition of the galactic center star cluster. Population analysis from adaptive optics narrow band spectral energy distributions. *Astronomy & Astrophysics*, 499:483–501, May 2009. doi: 10.1051/0004-6361/200811497.
- S. Chandrasekhar. *An introduction to the study of stellar structure*. 1967.
- C. Charbonnel, W. Däppen, D. Schaerer, P. A. Bernasconi, A. Maeder, G. Meynet, and N. Mowlavi. Grids of stellar models. VIII. From 0.4 to 1.0 $\{M_{sun}\}$ at $Z=0.020$ and $Z=0.001$, with the MHD equation of state. *aas*, 135:405–413, March 1999. doi: 10.1051/aas:1999454.
- R. M. Cheng and C. R. Evans. Relativistic effects in the tidal interaction between a white dwarf and a massive black hole in Fermi normal coordinates. *Phys. Rev. D.*, 87(10):104010, May 2013. doi: 10.1103/PhysRevD.87.104010.
- Phillip Colella and Paul R Woodward. The piecewise parabolic method (ppm) for gas-dynamical simulations. *Journal of Computational Physics*, 54(1):174 – 201, 1984. ISSN 0021-9991. doi: [http://dx.doi.org/10.1016/0021-9991\(84\)90143-8](http://dx.doi.org/10.1016/0021-9991(84)90143-8). URL <http://www.sciencedirect.com/science/article/pii/0021999184901438>.
- J. L. Cooper, G. V. Bicknell, R. S. Sutherland, and J. Bland-Hawthorn. Starburst-Driven Galactic Winds: Filament Formation and Emission Processes. *The Astrophysical Journal*, 703:330–347, September 2009. doi: 10.1088/0004-637X/703/1/330.
- L. J. Dai, S. V. Fuerst, and R. Blandford. Quasi-periodic flares from star-accretion-disc collisions. *Monthly Notices of the Royal Astronomical Society*, 402:1614–1624, March 2010. doi: 10.1111/j.1365-2966.2009.16038.x.
- J. E. Dale, M. B. Davies, R. P. Church, and M. Freitag. Red giant stellar collisions in the Galactic Centre. *Monthly Notices of the Royal Astronomical Society*, 393: 1016–1033, March 2009. doi: 10.1111/j.1365-2966.2008.14254.x.
- M. B. Davies, R. Blackwell, V. C. Bailey, and S. Sigurdsson. The destructive effects of binary encounters on red giants in the Galactic Centre. *Monthly Notices of the Royal Astronomical Society*, 301:745–753, December 1998. doi: 10.1046/j.1365-8711.1998.02027.x.
- T. Do, A. M. Ghez, M. R. Morris, J. R. Lu, K. Matthews, S. Yelda, and J. Larkin. High Angular Resolution Integral-Field Spectroscopy of the Galaxy’s Nuclear Cluster: A Missing Stellar Cusp? *The Astrophysical Journal*, 703:1323–1337, October 2009. doi: 10.1088/0004-637X/703/2/1323.

- LM Dray, Andrew R King, and Melvyn B Davies. Young stars in the galactic centre: a potential intermediate-mass star origin. *Monthly Notices of the Royal Astronomical Society*, 372(1):31–44, 2006.
- L. J. Dursi. Bubble Wrap for Bullets: The Stability Imparted by a Thin Magnetic Layer. *The Astrophysical Journal*, 670:221–230, November 2007. doi: 10.1086/521997.
- L. J. Dursi and C. Pfrommer. Draping of Cluster Magnetic Fields over Bullets and Bubbles-Morphology and Dynamic Effects. *The Astrophysical Journal*, 677:993–1018, April 2008. doi: 10.1086/529371.
- A. Ernst, A. Just, and R. Spurzem. On the dissolution of star clusters in the Galactic Centre - I. Circular orbits. *Monthly Notices of the Royal Astronomical Society*, 399: 141–156, October 2009. doi: 10.1111/j.1365-2966.2009.15305.x.
- P. C. Fragile, P. Anninos, K. Gustafson, and S. D. Murray. Magnetohydrodynamic Simulations of Shock Interactions with Radiative Clouds. *The Astrophysical Journal*, 619:327–339, January 2005. doi: 10.1086/426313.
- R. Genzel and V. Karas. The Galactic Center. In V. Karas and G. Matt, editors, *IAU Symposium*, volume 238 of *IAU Symposium*, pages 173–180, April 2007. doi: 10.1017/S1743921307004929.
- R. Genzel, N. Thatte, A. Krabbe, H. Kroker, and L. E. Tacconi-Garman. The dark mass concentration in the central parsec of the milky way. *The Astrophysical Journal*, 472(1):153, 1996. URL <http://stacks.iop.org/0004-637X/472/i=1/a=153>.
- R. Genzel, F. Eisenhauer, and S. Gillessen. The Galactic Center massive black hole and nuclear star cluster. *Reviews of Modern Physics*, 82:3121–3195, October 2010. doi: 10.1103/RevModPhys.82.3121.
- A. M. Ghez, G. Duchêne, K. Matthews, S. D. Hornstein, A. Tanner, J. Larkin, M. Morris, E. E. Becklin, S. Salim, T. Kremenek, D. Thompson, B. T. Soifer, G. Neugebauer, and I. McLean. The First Measurement of Spectral Lines in a Short-Period Star Bound to the Galaxy’s Central Black Hole: A Paradox of Youth. *The Astrophysical Journal Letters*, 586:L127–L131, April 2003. doi: 10.1086/374804.
- A. M. Ghez, S. Salim, S. D. Hornstein, A. Tanner, J. R. Lu, M. Morris, E. E. Becklin, and G. Duchne. Stellar orbits around the galactic center black hole. *The Astrophysical Journal*, 620(2):744, 2005. URL <http://stacks.iop.org/0004-637X/620/i=2/a=744>.
- S. Gillessen, F. Eisenhauer, S. Trippe, T. Alexander, R. Genzel, F. Martins, and T. Ott. Monitoring Stellar Orbits Around the Massive Black Hole in the Galactic Center. *The Astrophysical Journal*, 692:1075–1109, February 2009. doi: 10.1088/0004-637X/692/2/1075.

- A. Gualandris and D. Merritt. Long-term Evolution of Massive Black Hole Binaries. IV. Mergers of Galaxies with Collisionally Relaxed Nuclei. *The Astrophysical Journal*, 744:74, January 2012. doi: 10.1088/0004-637X/744/1/74.
- Michael S Hjellming and Ronald F Webbink. Thresholds for rapid mass transfer in binary systems. i-polytropic models. *The Astrophysical Journal*, 318:794–808, 1987.
- V. Karas and L. Šubr. Orbital decay of satellites crossing an accretion disc. *Astronomy & Astrophysics*, 376:686–696, September 2001. doi: 10.1051/0004-6361:20011009.
- S. S. Kim and M. Morris. Dynamical Friction on Star Clusters near the Galactic Center. *The Astrophysical Journal*, 597:312–322, November 2003. doi: 10.1086/378347.
- R. I. Klein, C. F. McKee, and P. Colella. On the hydrodynamic interaction of shock waves with interstellar clouds. 1: Nonradiative shocks in small clouds. *The Astrophysical Journal*, 420:213–236, January 1994. doi: 10.1086/173554.
- A. Krabbe, R. Genzel, S. Drapatz, and V. Rotaciuc. A cluster of He I emission-line stars in the Galactic center. *The Astrophysical Journal Letters*, 382:L19–L22, November 1991. doi: 10.1086/186204.
- K. Kwak, D. B. Henley, and R. L. Shelton. Simulations of High-velocity Clouds. I. Hydrodynamics and High-velocity High Ions. *The Astrophysical Journal*, 739:30, September 2011. doi: 10.1088/0004-637X/739/1/30.
- Y. Levin and A. M. Beloborodov. Stellar Disk in the Galactic Center: A Remnant of a Dense Accretion Disk? *The Astrophysical Journal Letters*, 590:L33–L36, June 2003. doi: 10.1086/376675.
- U. Löckmann and H. Baumgardt. Tracing intermediate-mass black holes in the Galactic Centre. *Monthly Notices of the Royal Astronomical Society*, 384:323–330, February 2008. doi: 10.1111/j.1365-2966.2007.12699.x.
- J. R. Lu, A. M. Ghez, S. D. Hornstein, M. R. Morris, E. E. Becklin, and K. Matthews. A Disk of Young Stars at the Galactic Center as Determined by Individual Stellar Orbits. *The Astrophysical Journal*, 690:1463–1487, January 2009. doi: 10.1088/0004-637X/690/2/1463.
- M.-M. Mac Low, C. F. McKee, R. I. Klein, J. M. Stone, and M. L. Norman. Shock interactions with magnetized interstellar clouds. 1: Steady shocks hitting non-radiative clouds. *The Astrophysical Journal*, 433:757–777, October 1994. doi: 10.1086/174685.
- Morgan MacLeod, Enrico Ramirez-Ruiz, Sean Grady, and James Guillochon. Spoon-feeding giant stars to supermassive black holes: Episodic mass transfer from evolving stars and their contribution to the quiescent activity of galactic nuclei. *The Astrophysical Journal*, 777(2):133, 2013.

- T. Matsubayashi, J. Makino, and T. Ebisuzaki. Orbital Evolution of an IMBH in the Galactic Nucleus with a Massive Central Black Hole. *The Astrophysical Journal*, 656:879–896, February 2007. doi: 10.1086/510344.
- F. Najarro, D. J. Hillier, R. P. Kudritzki, A. Krabbe, R. Genzel, D. Lutz, S. Drapatz, and T. R. Geballe. The nature of the brightest galactic center HeI emission line star. *Astronomy & Astrophysics*, 285:573–584, May 1994.
- S. Nayakshin, J. Cuadra, and R. Sunyaev. X-ray flares from Sgr A*: Star-disk interactions? *Astronomy & Astrophysics*, 413:173–188, January 2004. doi: 10.1051/0004-6361:20031537.
- J. Nittmann, S. A. E. G. Falle, and P. H. Gaskell. The dynamical destruction of shocked gas clouds. *Monthly Notices of the Royal Astronomical Society*, 201:833–847, December 1982.
- C. Norman and J. Silk. The dynamics and fueling of active nuclei. *The Astrophysical Journal*, 266:502–515, March 1983. doi: 10.1086/160798.
- J. P. Ostriker. Viscous drag on an accretion disk due to an embedded stellar system. *The Astrophysical Journal*, 273:99–104, October 1983. doi: 10.1086/161351.
- T. Paumard, R. Genzel, F. Martins, S. Nayakshin, A. M. Beloborodov, Y. Levin, S. Trippe, F. Eisenhauer, T. Ott, S. Gillessen, R. Abuter, J. Cuadra, T. Alexander, and A. Sternberg. The Two Young Star Disks in the Central Parsec of the Galaxy: Properties, Dynamics, and Formation. *The Astrophysical Journal*, 643:1011–1035, June 2006. doi: 10.1086/503273.
- B. Paxton, L. Bildsten, A. Dotter, F. Herwig, P. Lesaffre, and F. Timmes. Modules for Experiments in Stellar Astrophysics (MESA). *The Astrophysical Journal Supplement*, 192:3, January 2011. doi: 10.1088/0067-0049/192/1/3.
- J. J. Perry and R. Williams. Accretion discs in active galactic nuclei - Tell-tale signs of the nuclear star cluster? *Monthly Notices of the Royal Astronomical Society*, 260:437–452, January 1993.
- S. F. Portegies Zwart, H. Baumgardt, S. L. W. McMillan, J. Makino, P. Hut, and T. Ebisuzaki. The Ecology of Star Clusters and Intermediate-Mass Black Holes in the Galactic Bulge. *The Astrophysical Journal*, 641:319–326, April 2006. doi: 10.1086/500361.
- K. P. Rauch. Dynamical evolution of star clusters around a rotating black hole with an accretion disc. *Monthly Notices of the Royal Astronomical Society*, 275:628–640, August 1995.
- G. Schaller, D. Schaerer, G. Meynet, and A. Maeder. New grids of stellar models from 0.8 to 120 solar masses at $Z = 0.020$ and $Z = 0.001$. *aas*, 96:269–331, December 1992.

- N. I. Shakura and R. A. Sunyaev. Black holes in binary systems. Observational appearance. *Astronomy & Astrophysics*, 24:337–355, 1973.
- Gregory A Shields. The extraordinary abundances of quasar broad absorption line regions: A matter of novae? *The Astrophysical Journal Letters*, 461(1):L9, 1996.
- M.-S. Shin, J. M. Stone, and G. F. Snyder. The Magnetohydrodynamics of Shock-Cloud Interaction in Three Dimensions. *The Astrophysical Journal*, 680:336–348, June 2008. doi: 10.1086/587775.
- Gary A Sod. A survey of several finite difference methods for systems of nonlinear hyperbolic conservation laws. *Journal of Computational Physics*, 27(1):1 – 31, 1978. ISSN 0021-9991. doi: [http://dx.doi.org/10.1016/0021-9991\(78\)90023-2](http://dx.doi.org/10.1016/0021-9991(78)90023-2). URL <http://www.sciencedirect.com/science/article/pii/0021999178900232>.
- D. Syer, C. J. Clarke, and M. J. Rees. Star-disc interactions near a massive black hole. *Monthly Notices of the Royal Astronomical Society*, 250:505–512, June 1991.
- A. Tanner, D. F. Figer, F. Najarro, R. P. Kudritzki, D. Gilmore, M. Morris, E. E. Becklin, I. S. McLean, A. M. Gilbert, J. R. Graham, J. E. Larkin, N. A. Levenson, and H. I. Teplitz. High Spectral Resolution Observations of the Massive Stars in the Galactic Center. *The Astrophysical Journal*, 641:891–904, April 2006. doi: 10.1086/500498.
- S Trippe, S Gillessen, OE Gerhard, H Bartko, TK Fritz, HL Maness, F Eisenhauer, F Martins, T Ott, K Dodds-Eden, et al. Kinematics of the old stellar population at the galactic centre. *Astronomy & Astrophysics*, 492(2):419–439, 2008.
- EY Vilkoviskij and B Czerny. The role of the central stellar cluster in active galactic nuclei-i. semi-analytical model. *Astronomy & Astrophysics*, 387(3):804–817, 2002.
- J. C. Wheeler, M. Lecar, and C. F. McKee. Supernovae in binary systems. *The Astrophysical Journal*, 200:145–157, August 1975. doi: 10.1086/153771.
- Paul Woodward and Phillip Colella. The numerical simulation of two-dimensional fluid flow with strong shocks. *Journal of Computational Physics*, 54(1):115 – 173, 1984. ISSN 0021-9991. doi: [http://dx.doi.org/10.1016/0021-9991\(84\)90142-6](http://dx.doi.org/10.1016/0021-9991(84)90142-6). URL <http://www.sciencedirect.com/science/article/pii/0021999184901426>.
- A. S. Zentsova. A possible mechanism of jet formation in the nuclei of radio galaxies. *apss*, 95:459–462, September 1983. doi: 10.1007/BF00653649.
- W. H. Zurek, A. Siemiginowska, and S. A. Colgate. Star-disk collisions and the origin of the broad lines in quasars. *The Astrophysical Journal*, 434:46–53, October 1994. doi: 10.1086/174703.