Tidally-induced thermonuclear Supernovae

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Abstract. We discuss the results of 3D simulations of tidal disruptions of white dwarfs by moderate-mass black holes as they may exist in the cores of globular clusters or dwarf galaxies. Our simulations follow self-consistently the hydrodynamic and nuclear evolution from the initial parabolic orbit over the disruption to the build-up of an accretion disk around the black hole. For strong enough encounters (pericentre distances smaller than about 1/3 of the tidal radius) the tidal compression is reversed by a shock and finally results in a thermonuclear explosion. These explosions are not restricted to progenitor masses close to the Chandrasekhar limit, we find exploding examples throughout the whole white dwarf mass range. There is, however, a restriction on the masses of the involved black holes: black holes more massive than $2 \times 10^5 \, M_\odot$ swallow a typical $0.6 \, M_\odot$ white dwarf before their tidal forces can overwhelm the star’s self-gravity. Therefore, this mechanism is characteristic for black holes of moderate masses. The material that remains bound to the black hole settles into an accretion disk and produces an X-ray flare close to the Eddington limit of $L_{\text{Edd}} \approx 10^{41}$ erg/s $(M_{\text{bh}}/1000 \, M_\odot)$, typically lasting for a few months. The combination of a peculiar thermonuclear supernova together with an X-ray flare thus whistle-blow the existence of such moderate-mass black holes. The next generation of wide field space-based instruments should be able to detect such events.

1. Introduction

Two classes of black holes are established beyond reasonable doubt: black holes of a few solar masses ("stellar-mass") make themselves known by interacting with a companion star (McClintock & Remillard 2003) and "supermassive" black holes with masses of $10^6 - 10^{10} \, M_\odot$ seem to lurk in the centres of most, if not all galaxies, see e.g. (Kormendy & Richstone 1995; Ferrarese & Merritt 2000). A third class, so-called "intermediate-mass black holes" (IMBH) with masses of $\sim 1000 \, M_\odot$, represents a plausible, yet to date still missing link. The evidence for their existence is mounting, but to date it is not entirely conclusive. Based on kinematical studies Gerssen et al. (Gerssen et al 2002; 2003) have suggested the presence of a $3.9 \times 10^3 \, M_\odot$ black hole in the core of the globular cluster M15. More recently, there were further reports on IMBHs in the globular clusters NGC 2808 (Maccarone & Servillat 2008) and omegaCen (Noyola et al. 2008). Additional evidence comes from ultraluminous, compact X-ray sources in young star clusters (Zezas et al. 2002; Pooley & Rappaport 2006) and from n-body simulations (Portegies et al. 2004) that indicate that runaway collisions in dense young star clusters can produce rapidly growing black holes. None of the above arguments is strong enough to close the case, but their different nature gives this hypothesis credibility.

At the very large number densities in the environments that may harbor such black holes
stars are disrupted at a rate of \( \sim 10^{-7} \text{yr}^{-1} \) \( M_{\text{bh,3}}^{4/3} n_{*,6} \sigma_{10}^{-1} (R_{\text{per}}/R_{t}) \), where \( M_{\text{bh,3}} \) is the black hole mass in units of 1000 \( M_{\odot} \); \( n_{*,6} \) is the central stellar density in units of \( 10^6 \text{pc}^{-3} \); \( \sigma_{10} \) the velocity dispersion in \( 10 \text{km s}^{-1} \) and \( R_{\text{per}} \) is the distance of closest approach. The quantity \( R_{t} = (M_{\text{bh}}/M_{*})^{1/3} R_{*} \) is the tidal radius, the approximate separation where the hole’s tidal field wins the battle against the star’s self-gravity. It is proportional to the stellar radius \( R_{*} \), but only grows \( \propto M_{\text{bh}}^{1/3} \), i.e. substantially slower than the gravitational radius, \( R_{S} = 2GM_{\text{bh}}/c^2 \), of the black hole. As a consequence, too massive black holes, \( M_{\text{bh}} > M_{\text{bh,lim}} \approx 2.5 \times 10^5 M_{\odot} R_{\text{wd,9}}^{3/2} M_{\text{wd,0.6}}^{-1/2} \) will swallow stars before disrupting them. Here, \( R_{\text{wd,9}} \) is the white dwarf radius in \( 10^9 \text{cm} \) and \( M_{\text{wd,0.6}} \) its mass in units of 0.6 \( M_{\odot} \). Thus, white dwarfs with their small radii and their (at least in principle) available nuclear fuel can only be tidally squeezed and disrupted by black holes of moderate masses. Therefore they are precious tools to probe the existence of this type of black hole.

Luminet & Pichon (1989) were the first to discuss the tidal disruption of white dwarfs by black holes in the context of the affine star model (Carter & Luminet 1983; 1985). Wilson and Mathews (2004) believe that general relativistic effects may lead to a tidal ignition even for supermassive black holes and at separations of many gravitational radii. A hydrodynamic simulation with a Newtonian Adaptive Lagrangian Eulerian (ALE) code was performed recently (Dearborn et al. 2005) where the gravitational constant was adjusted to mimic general relativistic effects. We have recently performed a large set of 3D hydrodynamic simulations (Rosswog et al. 2008a; 2008d) that incorporate the nuclear energy generation self-consistently with the hydrodynamics.

2. Ingredients for the simulations

Here we briefly summarize the ingredients of our simulations, both in terms of physics and numerical methods. We described the numerical aspects in Rosswog et al. (2008b) and in Rosswog et al. (2008d) we concentrated on the physics and the astrophysical implications of such tidal disruptions.

We use the smoothed particle hydrodynamics method (SPH) to follow the hydrodynamic evolution of the white dwarf matter. Being completely Lagrangian and conserving mass, energy, momentum and angular momentum by construction the method is ideal for the study of such a violent stellar disruption. General reviews on the method can be found in Benz (1990a), Monaghan (1992) and Monaghan (2005), our particular implementation is documented in Rosswog et al. (2008b). We calculate the forces from self-gravity via a binary tree (Benz et al. 1990b) and those from the central black hole via a relativistic pseudo potential (Paczynski & Wiita 1980), details of how the singularity is treated numerically are laid out in Rosswog (2005a). We close the system of hydrodynamics equations via the HELMHOLTZ equation of state (EOS) (Timmes & Swesty 2000). It accepts an externally calculated chemical composition, facilitating the coupling to nuclear reaction networks. The electron-/positron equation of state makes no assumptions about the degree of degeneracy or relativity, the exact expressions are integrated numerically and are subsequently tabulated. The interpolation in this table enforces thermodynamic consistency by construction (Timmes & Swesty 2000). The nuclei in the gas are treated as a Maxwell-Boltzmann gas, the photons as blackbody radiation. Most importantly in this context, we couple a minimal nuclear reaction network (Hix et al. 1998) to the hydrodynamics. Throughout this simulation set we assume a uniform nuclear composition across the white dwarfs. Stars with masses \(< 0.6 M_{\odot}\) are instantiated as pure helium, more massive stars are modeled with a mass fraction of 50% carbon and 50% oxygen. All simulations are started from parabolic orbits, the strength of an encounter is parametrized by the penetration factor \( \beta = R_{t}/R_{\text{per}} \). For more details we refer the interested reader to Rosswog et al. (2008b, 2008d).
3. Results

3.1. Explosion mechanism

The tidal gravitational field is, to lowest order, determined by the second-order tidal tensor and the third-order deviation tensor. The latter determines the deviation of an extended body from a point particle trajectory of the same mass. The tidal tensor determines how the fluid will be shaped. It possesses one positive and two negative eigenvalues, see e.g. Brassart & Luminet (2008), and, as a consequence, the tidal field stretches the star in one eigen-direction and compresses it along the other two. Most severely, the star is compressed perpendicular to the orbital plane, this process halts when a shock forms (Kobayashi et al. 2004a; Brassart & Luminet 2008; Rosswog et al. 2008d) that reverts the compression into an expansion. For deep enough penetrations matter reaches nuclear statistical equilibrium, see Fig. 1, upper right panel. The star is squeezed through a point of maximum compression on a time scale of \( \tau_{\text{comp}} \approx \frac{R_{\text{wd}}}{v_p} \approx \frac{0.2s}{M_{\text{wd,0.6}}} \left( R_{\text{wd,9}} \right)^{3/2} \left( M_{\text{bh,3}} \right)^{-1/3} \), where \( v_p \approx \frac{R_{\text{g}}}{R_p} \frac{1}{c} \sim 5 \times 10^5 \text{cm s}^{-1} \frac{M_{\text{wd,0.6}}}{R_{\text{wd,9}}} \left( M_{\text{bh,3}} \right)^{1/3} \) is the peri-centre passage velocity. This velocity exceeds thermonuclear flame speeds by orders of magnitude, therefore, flame propagation effects can be safely neglected. The compression time scale needs to be compared to the dynamical time scale of the star, \( \tau_{\text{dyn}} = (G\bar{\rho})^{-1/2} \approx 7.2 \text{s} \left( M_{\text{wd,0.6}} \right)^{1/2} \left( R_{\text{wd,9}} \right)^{3}, \) with \( \bar{\rho} \) being the average stellar density and to the nuclear reaction time scale, \( \tau_{\text{nuc}} \). Only for \( \tau_{\text{nuc}} \ll \tau_{\text{comp}}, \tau_{\text{dyn}} \) can a substantial nuclear energy release be expected. Our large simulation set (Rosswog et al. 2008d) shows that white dwarfs of all masses can be thermonuclearly exploded provided that the penetration factor exceeds \( \beta \approx 3 \). For definiteness, we illustrate here the results at the example of a typical 0.6 M\(_\odot\) carbon-oxygen (CO) white dwarf that passes a 500 M\(_\odot\) black hole with a penetration factor of \( \beta = 5 \), see Fig. 1.

3.2. Nucleosynthesis

Nucleosynthesis is triggered predominantly in the point of maximum compression, see Fig. 1, upper right panel, the concomitant nuclear energy release inflates a hot bubble in the debris centre, see Fig. 1, lower panels. The high-density centre of the star produces an iron-group core of 0.18 M\(_\odot\), if mainly composed of \(^{56}\text{Ni}\) this amount is comparable, but at the lower end of what is deduced for standard type Ia supernovae (Mazzali et al. 2007). The iron core is surrounded by a 0.21 M\(_\odot\) shell of silicon-group elements which in turn is covered by a sheath of unburned carbon-oxygen material, see Fig. 2. In reality, such a disruption would result in even stronger carbon-enhanced outer layers than shown in Fig. 2. For simplicity, we have instantiated our initial carbon oxygen white dwarf models (\( M_{\text{WD}} \geq 0.6 \text{M}_\odot \)) as homogeneously mixed stars with a 50% mass fraction of each nucleus. While such internal chemical profiles are likely accurately realized in nature in very massive white dwarfs (\( \sim 1 \text{M}_\odot \)) (Mazzitelli & Dantona 1986), for lower masses the gravitational thermalization of the interior during the cooling phase produces oxygen-enhanced stellar cores surrounded by very carbon-rich mantles (\( X_C \sim 0.8 \)). The exact radial distribution depends on the exact value of \(^{12}\text{C}(\alpha, \gamma)^{16}\text{O} \) rate and the details of how convection proceeds (Mazzitelli & Dantona 1986; Salasir et al. 1997; Straniro et al. 2003), but this general stratification tendency is well-established. Thus, the disruption of a standard 0.6 M\(_\odot\) white dwarf should produce a highly carbon-enriched remnant atmosphere.

We found exploding examples throughout the whole white dwarf mass range. An extreme case is a low-mass white dwarf that can (due to its large stellar and correspondingly large tidal radius) be sent very deeply into the tidal radius of a black hole. A 0.2 M\(_\odot\), pure helium white dwarf disrupted by a 1000 M\(_\odot\) black hole (\( \beta = 12 \)) produced an explosion with about 0.03 M\(_\odot\) of iron-group elements. At the other extreme, a 1.2 M\(_\odot\) CO white dwarf exploded with 0.66 M\(_\odot\)

\(^1\) Note that our network uses element groups, individual isotopes would need to be recovered in a post-processing step with larger network.
Figure 1. Density (left column) and temperature (right column) evolution during the disruption of 0.6 M$_\odot$ CO white dwarf by a 500 M$_\odot$ black hole. The distance of closest approach was 1/5 of the tidal radius.

of iron group elements after passing a 500 M$_\odot$ black hole with $\beta = 2.6$. For more details and examples, the interested reader should consult Rosswog et al. (2008d). A detailed comparison of the lightcurves of tidally-induced supernovae and "normal" type Ia supernovae is currently being prepared (Kasen et al. 2008).

3.3. Accompanying signatures
If the release of nuclear binding energy is disregarded, about half the stellar mass is ejected, the rest is still bound to the black hole and, in principle, available to be accreted. Nuclear energy release during pericentre passage can substantially increase the amount of unbound mass to about $\sim 65\%$ (Rosswog et al. 2008a). Before the energy contained in the bound matter can be released, an accretion disk has to form. On returning to the black hole, the orbits of the bound matter become focussed once more towards peri-center. The spread of specific energies across the accretion stream is very large (Rees 1988) so that matter that passes on the inside
Figure 2. Mass fractions resulting from the disruption of $0.6 \, M_{\odot}$ CO white dwarf by a $500 \, M_{\odot}$ black hole. The distance of closest approach was $1/5$ of the tidal radius.

of the stream, i.e. closer to the black hole, is substantially stronger bound and subsequently only reaches moderate apocentre distances while matter on the outside track is relaunched into a substantially wider orbit. Thus, after having passed the hole for the second time, the matter stream spreads in a fan-like manner (Rees 1988; Rosswog et al. 2008d). It subsequently collides with the still infalling material and this self-interaction produces an angular momentum redistribution shock that circularizes the forming accretion disk, see e.g. Fig. 4 in (Rosswog et al. 2008a). In the early stages, mass is fed towards the black hole at a rate that carries the imprint of the internal structure of the star (Lodato et al. 2008; Ramirez-Ruiz & Rosswog 2008), at later stages the rate falls off $\propto t^{-5/3}$ (Rees 1988, Phinney 1989). Once a disk has formed, it evolves under the influence of viscosity, radiatively driven winds and the fallback rate by which it is fed. We expect a luminosity that is comparable to the Eddington value, $L_{\text{Edd}} \approx 10^{44} \text{erg/s} \left(\frac{M_{\text{bh}}}{1000 \, M_{\odot}}\right)$, typically lasting for a few months.
4. Summary and discussion

We have explored in detail the fate of white dwarfs that approach a moderately-massive black hole close enough to become tidally disrupted. Above a limiting mass of $\sim 10^5 M_\odot$, the detailed value depending on the white dwarf, the black hole swallows the star as a whole before disrupting it. Thus white dwarfs represent a precious tool to probe the existence of moderate-mass black holes. White dwarfs that penetrate the tidal radius deeply enough are heated by the tidal compression and ensuing shock to the temperatures of nuclear statistical equilibrium. In favorable cases more than the gravitational self-binding energy of the star can be released via nuclear reactions thus triggering a thermonuclear explosion of the white dwarf. The amount of iron-group nuclei produced is rather sensitive to the densities at which nuclear burning occurs, and therefore to the white dwarf mass. The amount produced in the exploding cases of our simulation set (Rosswog et al. 2008d) ranges from 0.03 $M_\odot$ for a 0.2 $M_\odot$ pure helium white dwarf to 0.66 $M_\odot$ for a 1.2 $M_\odot$ carbon-oxygen white dwarf, i.e. if composed of mainly $^{56}$Ni the favorable cases produce amounts comparable to standard type Ia supernovae (Mazzali et al. 2007).

These tidally-induced supernovae are, however, in several respects different from what is considered a “normal” type Ia supernova. First, they are not restricted to progenitor masses close to the Chandrasekhar limit. We find exploding examples throughout the full explored mass range from 0.2 to 1.2 $M_\odot$. Typical examples of these explosions are close to peak of the white dwarf mass distribution, i.e. near 0.6 $M_\odot$, or slightly above this value, since in the dense stellar environments around such black holes close encounters between stars may lead to mass segregation (Binney & Tremaine 2008). Thus the average progenitor will be less massive than for a normal type Ia. Second, and closely related to the first point, the progenitor composition is not restricted to carbon-oxygen. Also pure helium white dwarfs can explode via this mechanism, but since white dwarfs near and slightly beyond the peak of the mass distribution are thought to consist of carbon and oxygen this is the most common progenitor composition. Due to the initial chemical layering of the white dwarfs, the outer shells of the most common explosion remnants consist of unburned, highly carbon-enriched ($X_C \sim 0.8$) material. Third, the remnant geometry is most likely much less spherical than a standard type Ia, therefore the optical lightcurve should be rather unique as a result of the radiating material being highly squeezed into the orbital plane. The large velocities of the ejected debris ($> 10^4$ km/s) should produce large Doppler shifts. And last but not least, this peculiar type of thermonuclear supernova is accompanied by an X-ray flare close to the Eddington luminosity that lasts for a few months.

The estimated event rates for this type of transient are $\sim 10^{-3}$ of the type Ia supernova rate. Though being substantially less frequent, they occur often enough to warrant a search for this new class of optical transient. Upcoming supernova searches hope to discover several thousand to several hundred thousand type Ia-like events (Riess & Livio 2006; Aldering et al. 2007) per year. Chances are good to find examples of tidally-induced thermonuclear supernovae among them. Maybe, the recently detected carbon-rich transient SCP 06F6 accompanied by an X-ray signal (Gaensicke et al. 2008) is already the first example for this class of object.

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References
Aldering G Kim A G Kowalski M Linder E V Perlmutter S 2007 Snapping supernovae at z > 1 7 Astroparticle Physics 27 213–225
Benz W 1990a Smooth particle hydrodynamics: A review in: J Buchler (Ed ) Numerical Modeling of Stellar Pulsations Kluwer Academic Publishers Dordrecht p 269
Benz W Bowers R Cameron A Press W 1990b Dynamic mass exchange in doubly degenerate binaries i - 0 9 and 1 2 solar mass stars ApJ 348 647
Binney J Tremaine S 2008 Galactic Dynamics: Second Edition ISBN 978-0-691-13026-2 (HB) Published by Princeton University Press Princeton NJ USA
Brassart M Luminet J 2008 Shock waves in tidally compressed stars by massive black holes A&A 481 259–277
Carter B Luminet J P 1983 Tidal compression of a star by a large black hole I Mechanical evolution and nuclear energy release by proton capture A&A 121 97–113
Carter B Luminet J P 1985 Mechanics of the affine star model M.N.R.A.S. 212 23–55
Dearborn D S P Wilson J R Mathews G J 2005 Relativistically Compressed Exploding White Dwarf Model for Sagittarius A East ApJ 630 309–320
Ferrarese L Merritt D 2000 A Fundamental Relation between Supermassive Black Holes and Their Host Galaxies ApJL 539 L9–L12
Gaensicke B T Levan A J Marsh T R Wheatley P J 2008 SCP06F6: A carbon-rich extragalactic transient at redshift z 0 14 ArXiv e-prints
Gerssen J van der Marel R P Gebhardt K Guhathakurta P Peterson R C Pryor C 2002 Hubble Space Telescope Evidence for an Intermediate-Mass Black Hole in the Globular Cluster M15 II Kinematic Analysis and Dynamical Modeling AJ 124 3270–3288
Gerssen J van der Marel R P Gebhardt K Guhathakurta P Peterson R C Pryor C 2003 Addendum: Hubble Space Telescope Evidence for an Intermediate-Mass Black Hole in the Globular Cluster M15 II Kinematic Analysis and Dynamical Modeling AJ 125 376–377
Hix W R Khokhlov A M Wheeler J C Thielemann F -K 1998 The Quasi-Equilibrium-reduced alpha -Network ApJ 503 332
Kasen D Ramirez-Ruiz E Rosswog S 2008 in preparation
Kobayashi S Laguna P Phinney E S Mészáros P 2004 Gravitational Waves and X-Ray Signals from Stellar Disruption by a Massive Black Hole ApJ 615 855–865
Kormendy J Richstone D 1995 Inward Bound-The Search For Supermassive Black Holes In Galactic Nuclei Ann Rev Astron Astrophys 33 581
Lodato G King A R Pringle J E 2008 Stellar disruption by a supermassive black hole: is the light curve really proportional to $t^{\frac{-5}{3}}$? ArXiv e-prints
Luminet J P Pichon B 1989 Tidally-detonated nuclear reactions in main sequence stars passing near a large black hole A&A 209 85–102
Maccarone T J Servillat M 2008 Radio observations of NGC 2808 and other globular clusters: constraints on intermediate-mass black holes M.N.R.A.S. 389 379–384
McClintock J E Remillard R A 2003 Black Hole Binaries ArXiv Astrophysics e-prints
Mazzali P A R¨opke F K Benetti S Hillebrandt W 2007 A Common Explosion Mechanism for Type Ia Supernovae Science 315 825–
Mazzitelli I Dantona F 1986 The relation between initial and minimum final white dwarf mass for Population I stars ApJ 311 762–773
Monaghan J J 1992 Smoothed particle hydrodynamics Ann Rev Astron Astrophys 30 543
Monaghan J J 2005 Smoothed particle hydrodynamics Reports on Progress in Physics 68 1703–1759
Noyola E Gebhardt K Bergmann M 2008 Gemini and Hubble Space Telescope Evidence for an Intermediate-Mass Black Hole in ω Centauri ApJ 676 1008–1015
Paczynski B Wiita B 1980 Thick accretion disks and superficial luminosities 88 23
Phinney E. S 1989 Manifestations of a Massive Black Hole in the Galactic Center in: M Morris (Ed ) IAU Symp 136: The Center of the Galaxy p 543
Pooley D Rappaport S 2006 X-Rays from the Globular Cluster G1: Intermediate-Mass Black Hole or Low-Mass X-Ray Binary? ApJL 644 L45–L48
Portegies Zwart S F Baumgardt H Hut P Makino J McMillan S L W 2004 Formation of massive black holes through runaway collisions in dense young star clusters Nature 428 724–726
Ramirez-Ruiz E Rosswog S 2008 The star ingesting luminosity of intermediate mass black holes in globular clusters ArXiv e-prints
Rees M 1988 Tidal disruption of stars by black holes of 10 to the 10 to the 8th solar masses in nearby galaxies Nature 333 523–528
Riess A G Livio M 2006 The First Type Ia Supernovae: An Empirical Approach to Taming Evolutionary Effects ApJ 656 604–608
in Dark Energy Surveys from SNe Ia at $z>2$ ApJ 648 884–889
Rosswog S 2005 Mergers of Neutron Star-Black Hole Binaries with Small Mass Ratios: Nucleosynthesis Gamma-Ray Bursts and Electromagnetic Transients ApJ 634 1202–1213
Rosswog S Ramirez-Ruiz E Hix R 2008a Atypical thermonuclear supernovae from tidally crushed white dwarfs ApJ 679 1385
Rosswog S Ramirez-Ruiz E Hix R 2008d Tidal disruption and ignition of white dwarfs by moderately massive black holes submitted to ApJ
Rosswog S Ramirez-Ruiz E Hix R 2008 Simulating black hole white dwarf encounters Comp Phys Comm
Salaris M Dominguez I Garcia-Berro E Hernanz M Isern J Mochkovitch R 1997 The Cooling of CO White Dwarfs: Influence of the Internal Chemical Distribution ApJ 486 413–+
Straniero O Domínguez I Imbriani G Piersanti L 2003 The Chemical Composition of White Dwarfs as a Test of Convective Efficiency during Core Helium Burning ApJ 583 878–884
Timmes F X Swesty F D 2000 The Accuracy Consistency and Speed of an Electron-Positron Equation of State Based on Table Interpolation of the Helmholtz Free Energy ApJS 126 501–516
Wilson J R Mathews G J 2004 White Dwarfs near Black Holes: A New Paradigm for Type I Supernovae ApJ 610 368–377
Zezas A Fabbiano G Rots A H Murray S S 2002 Chandra Observations of “The Antennae” Galaxies (NGC 4038/4039) III X-Ray Properties and Multiwavelength Associations of the X-Ray Source Population ApJ 577 710–725