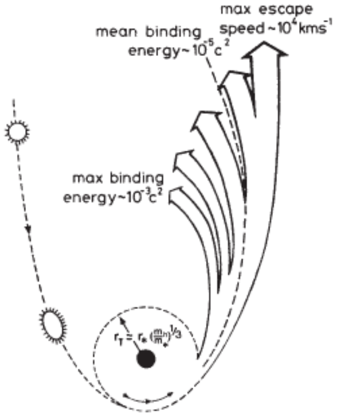
How does the debris from a stellar tidal disruption join an accretion flow?

Roseanne M. Cheng [1]
Hotaka Shiokawa [1], Julian H. Krolik [1], Tsvi Piran [2], Scott C. Noble [3]

[1]Department of Physics and Astronomy, Johns Hopkins University,
[2]Racah Institute of Physics, The Hebrew University of Jerusalem,
[3]Department of Physics and Engineering Physics, University of Tulsa

January 22, 2015

Tidal disruption events: traditional model of $t^{-5/3}$



Rees (1988)

Geometry of disk: $\sim 2R_T$

$$R_T = R_* \left(\frac{M_{\rm BH}}{M_*}\right)^{1/3}$$

$$a_{\min} = \frac{1}{2} R_T (M_{\rm BH}/M_*)^{1/3}$$

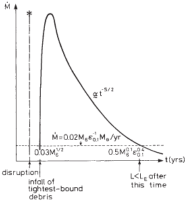
Accretion timescale

$$\tau_{\rm acc} \ll \tau_0 = P_{\rm orb}(a_{\min})$$

Gas is accreted after a few orbits because debris streams will focus at periastron and precess due to general relativity (shocks $\rightarrow \mathcal{O}(cR_g/R_T)$).

Classic theoretical expectations

Rate of first return of debris to periastron (Phinney, 1989)



$$\dot{M}_{\rm return} = \frac{dM}{d\epsilon}\frac{d\epsilon}{dt} = \frac{1}{3}\frac{M_*}{\tau_0}\left(\frac{t}{\tau_0}\right)^{-5/3}$$

IF quick entry into disk at R_T, THEN

$$\dot{M}_{\rm acc} = \dot{M}_{\rm return} \propto t^{-5/3}$$

AND IF efficient radiation, THEN

$$L = \epsilon \dot{M} c^2 \propto t^{-5/3}$$

BUT

$$L_{\rm peak}/L_{\rm Edd} \gg 1, \qquad M_{\rm BH} \lesssim 10^7 M_\odot$$ (Ulmer, 1997)

IF photosphere near ISCO, THEN

$$T \sim 10^5 K$$

Additional challenges to the $t^{-5/3}$-paradigm

Observational difficulties:

$\longrightarrow$ Radiation should be primarily in the UV (Rees, 1988)

$\longrightarrow$ Bolometric (Lodato & Rossi, 2011) and extinction corrections to lightcurve

Inconsistencies with classical theory and observed candidates:

(Cenko et al., 2012; Gezari et al., 2012; Chornock et al., 2014; Holoien et al., 2014; Arcavi et al., 2014; Vinko et al., 2015)

- Peak luminosities are lower than classical expectation:

$$L_{\rm obs} \sim 10^{43} - 10^{44} \mathrm{erg/s} \qquad \longleftrightarrow \qquad L_{\rm peak} \sim 5 \times 10^{46} \mathrm{erg/s}$$

- Temperature lower than classical expectation:

$$T_{\rm obs} \sim 10^4 K \qquad \longleftrightarrow \qquad T \sim 10^5 K$$

How do we explain the TDE candidates with jets? (observed in hard X-ray)

Detailed calculations of the accretion process are necessary

Current state of the theory

$\longrightarrow$ shocks at periastron are not efficient enough to circularize material

$$\tau_{\rm acc} \not< \tau_0 \qquad \text{(Kochanek, 1994; Guillochon et al., 2014)}$$

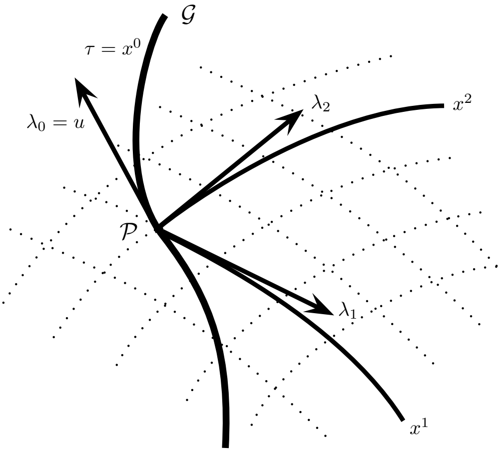
Mechanism by which tidal debris settles into accretion flow unknown

Our approach:

- simulate encounter from disruption to formation of accretion disk
- use general relativistic hydrodynamics (GRHD)

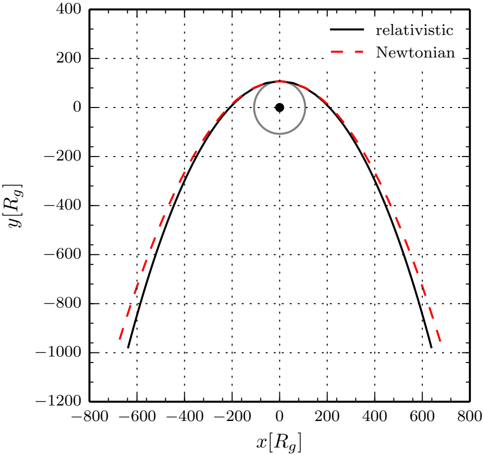
Tidal disruption computed in local and global frame

Simulate disruption of star by a Schwarzschild black hole and evolution of debris streams with general relativistic hydrodynamics



- **Local**: (initial data) relativistic (2PN) calculation in **FNC** frame following the star (Cheng & Evans, 2013)
- **Global**: local data as initial conditions for simulation in black hole frame with **Harm3d** full GRHD (**Shiokawa, Krolik, Cheng, Piran, Noble, 2014**)

Dynamic lengthscales/timescales depend on mass ratio

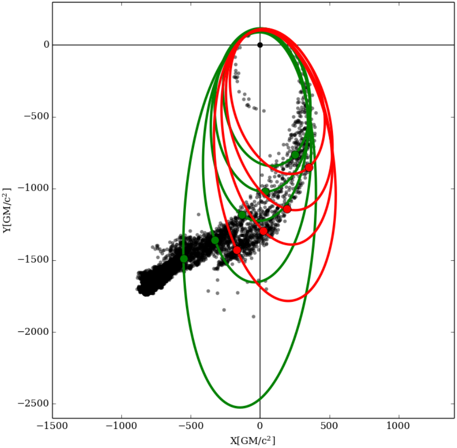


Choose parameters for modest computational expense

$$\begin{aligned} M_{\rm WD} &= 0.64 M_\odot \\ M_{\rm BH} &= 500 M_\odot \\ R_g &= G M_{\rm BH}/c^2 \\ R_p &= R_T = 107 R_g \\ a_{\rm min} &= 495 R_g \end{aligned}$$

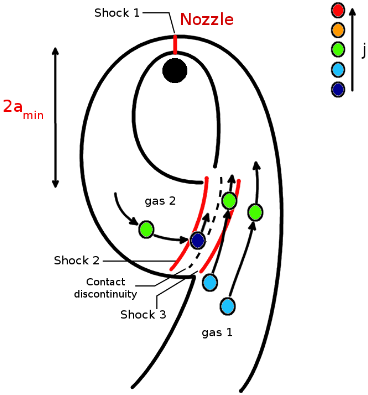
Initial conditions: stellar debris in global frame

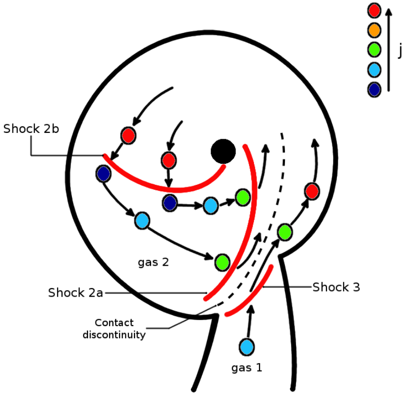
Swing in apsidal angle due to relativistic effects during disruption



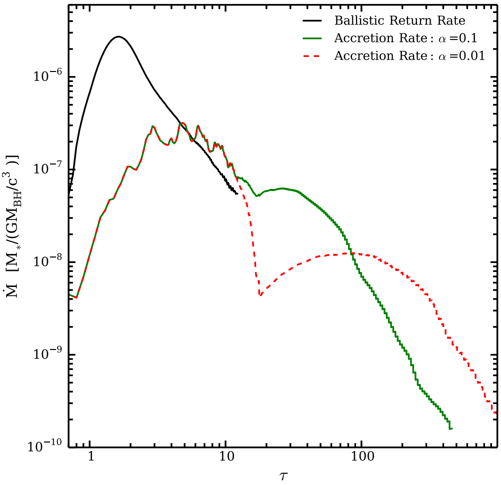
- Small PN effects (GR apsidal precession in stellar orbit and GR corrections to tidal stress) lead to strong shocks near orbital apocenters
- expected for main sequence star encounters (Cheng & Bogdanović,2014)

Results: shock formation (Shiokawa et al., 2014)





Results: Mass inflow rate (Shiokawa et al., 2014)

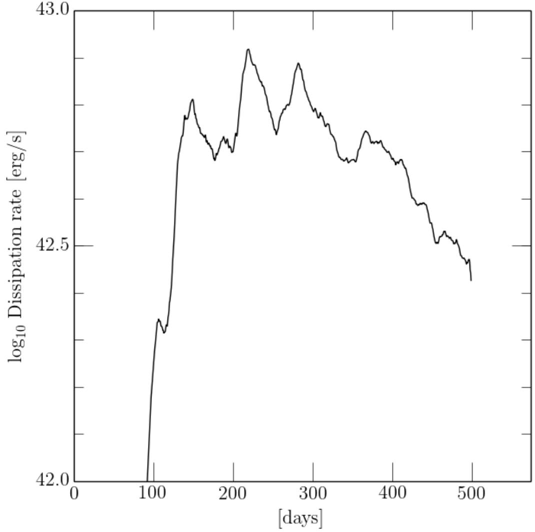


Accretion rate simulated in black hole frame for $\tau < 12$

Accretion rate extrapolated (analytic accretion theory) from simulation for $\tau > 12$

- $\dot{M}_{\rm peak}$ is 10% of classical expectation
- later, flatter peak $\tau_{\rm peak} \sim 3 - 8$

Heating rate in accretion disk formation



- Heating rate calculated from shocks in simulation
- Scaled to main sequence star disruption by $M_{\rm BH} = 10^6 M_\odot$
- Initially nozzle then apocenter shocks

Conclusions

- characteristic scale at which the tidal streams merge to form an accretion flow $a_{\min} \gg R_T$
- in addition to shock at nozzle, find existence of outer shocks
  $\longrightarrow$ largely due to relativistic effects
- accumulation of mass into accretion flow requires $\sim 5\tau_0$
- further time delay due to a larger disk than expected, which has a significantly longer inflow time
- $\dot{M}_{\rm peak}$ is 10% of classical expectation

Expect significant departures from classical expectations for the lightcurve associated with tidal disruptions