Hydrodynamic Simulations of Mass Accretion onto a Black Hole

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Accreting black hole systems such as X-ray binaries (black holes with a close stellar companion that provide the black hole its fuel) and active galactic nuclei (supermassive, accreting black holes at the center of galaxies) exhibit variability in their luminosity on many timescales ranging from milliseconds to tens of days, and even hundreds of days. The mechanism(s) driving this variability is poorly understood. We seek to employ numerical techniques to study accretion disks including more complicated physics traditionally ignored in the fluid equations describing accretion disks in order to more accurately understand their behavior over time, including variability, which cannot be done analytically. I present a proof-of-concept 3D global simulation using the grid-based, hydrodynamic code PLUTO, in which both serial and massively parallel computations are possible, of a simplified thin disk model about a central black hole. I also generate a simplistic synthetic light curve that displays the variability in luminosity of the simulation over time, a critical step in comparing to observational data. The ultimate goal will be to include radiation and evolve the simulation over a period of many days (a challenge for hydrodynamic codes) in order to study instabilities that arise due to a central, radiating source and to create a more sophisticated simulated light curve for comparison to observations.

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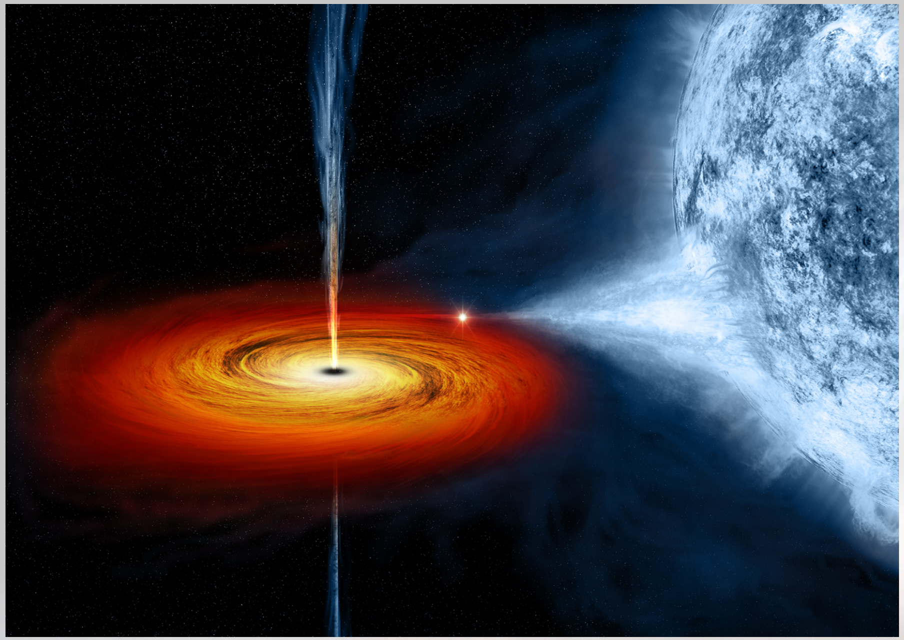
Background: Paramount Pictures, "Interstellar"

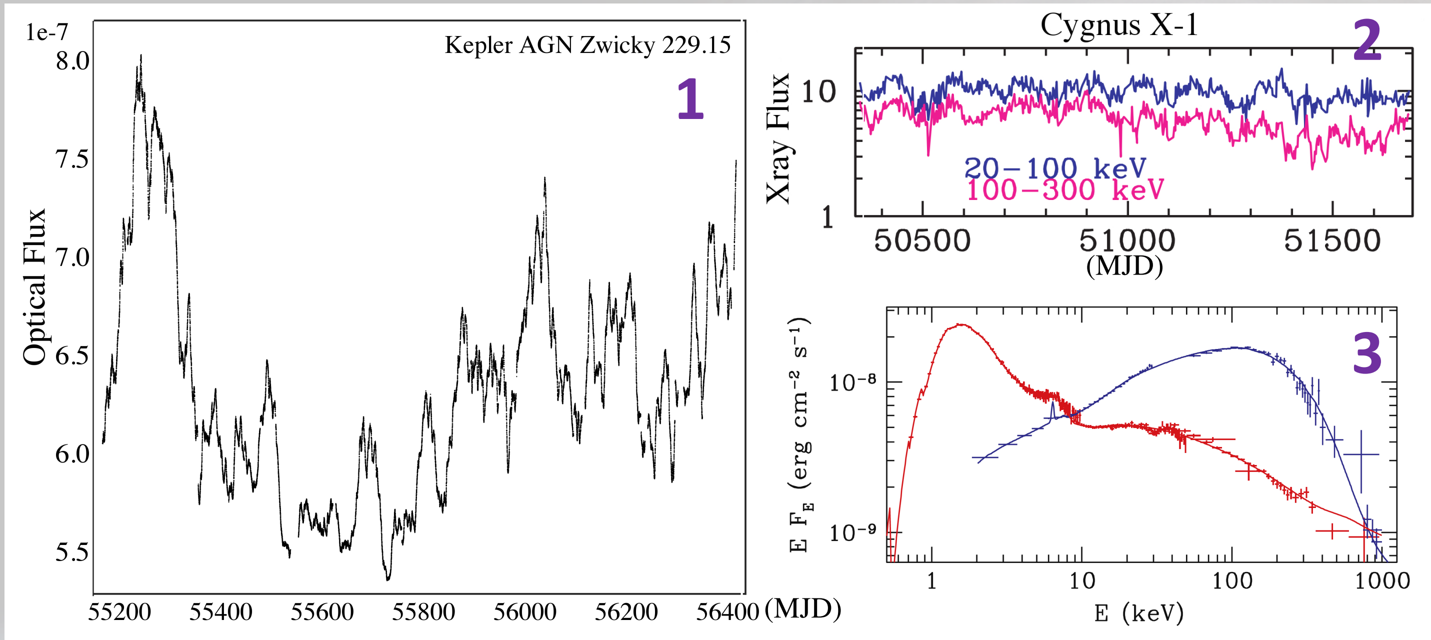
Background & Motivations: AGN and XRBs



***Left**: Artist's rendition of a black hole binary system; **Right**: Color composite of NGC 5128 by the ESA, with supermassive black hole ~55 million solar masses, showing its extensive radio jets; Both systems are powered by substantial accretion disks*

- X-ray binaries, or XRBs (a neutron star or black hole with a stellar companion) have masses comparable to the mass of our sun.
- Active Galactic Nuclei, or AGN (black holes at the center of galaxies, like our own), have masses 10^6 to 10^9 times that of our sun.
- Both are powered by the accretion of matter via a disk and exhibit similar variability in their lumonisity on multiple time scales, which give information about the physical mechanisms at play.
- Variability ranges from milliseconds up to hundreds of days.
- Variability persists across nearly all bandwidths of light.
- Recent work suggests a scaling relationship in accretion disk physics across the black hole mass scale (Scaringi et al., 2015)

Background & Motivations: The Source(s) of Variability



The variability in the optical band of the AGN Kepler Zwicky 229.15 over ~1,000 days

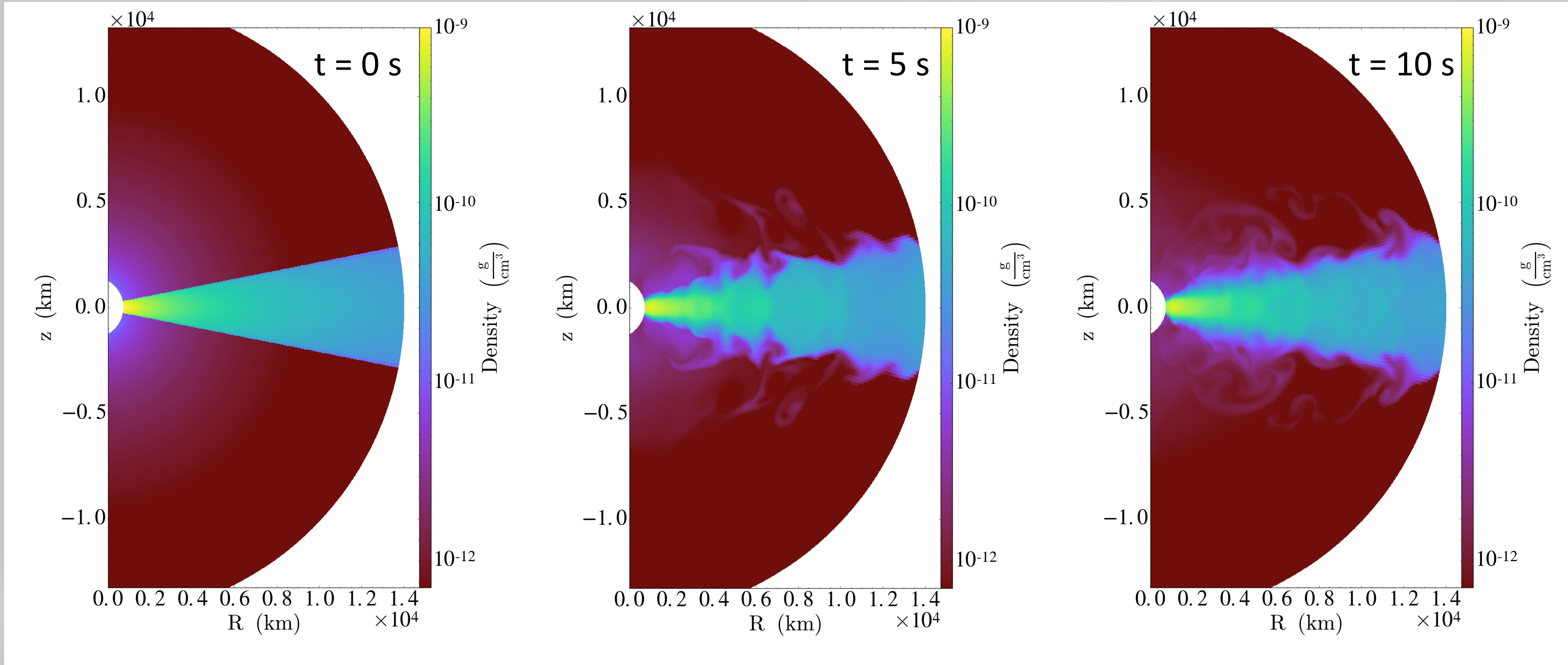
X-ray variability of ~1,500 days of Cygnus X-1 in 2 different energy bands – note the flux is on a log scale

”soft” (red) and “hard” (blue) spectral states of black-hole binary Cygnus X-1 at two different epochs

- Analytic studies of accretion disks make predictions aligned with some observations (red curve in **Figure 3**, but not blue)
- More accurate models require numerical analysis of Navier-Stokes equations including external torques
- There has been success in studying the role of magnetic fields (numerically) in accretion disk systems and how they relate to the viscosity mechanism in the disk. What other external effects can be studied?
- Radiation, not yet well studied, is known to have a significant impact on the dynamics (e.g. irradiation-driven warping) and cooling/heating mechanisms of accretion disks and long-term variability of AGN and XRBs
- **We must investigate the behaviors of accretion disks under the influence of radiation numerically and compare to observations & theory**

Figures: Kasliwal et al. (2015), Lachowicz et al. (2006), Done et al. (2007)

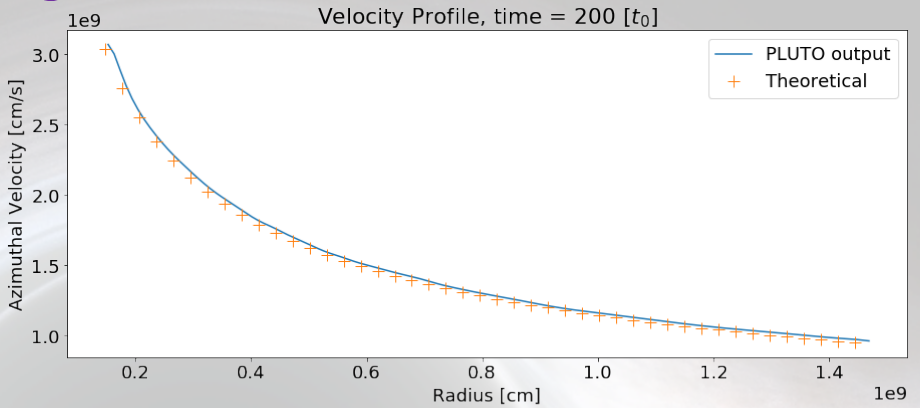
Accretion Disk Simulation using *PLUTO*



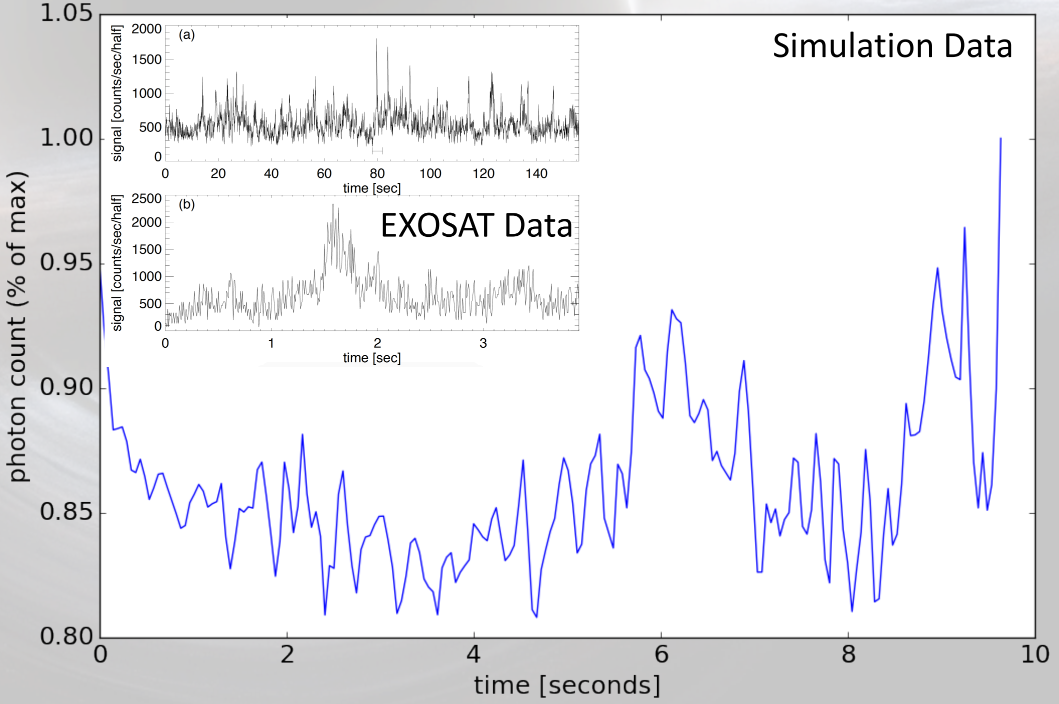
- *PLUTO*: A modular, hydrodynamical, grid-based code for computational astrophysics
- Start with pure hydrodynamics module to create a *proof-of-concept* simulation: optically thick, geometrically thin accretion disk obeying vertical hydrostatic equilibrium embedded in an optically thin polytropic corona; scaled of the disk modelled after XRB Cygnus X-1
- Evolved initial state for 260 time steps, where 1 step = 0.05 seconds, as exhibited above
- Shadmehri and Rammos (2010) showed that Kelvin-Helmholtz instability will arise at the interface of a disk and corona system – KH is observed in the simulation

Next Steps: Radiation & Magnetic Fields

- Creating a simulated light curve (flux vs. time)
  - Using python toolkit *yt* and function *YTRay*
  - Compute number of photons to leave through each column assuming each cell radiates like a blackbody; assume opacity dominated by electron scattering
  - **Result**: total flux from disk at each time step; time expensive
  - **Next steps**: more sophisticated radiative transfer treatment
- Simulation next steps:
  - Test with larger cluster at Drexel
  - Add in Kolb et al. 2013 radiation module to PLUTO
- Comparison to observations:
  - Perform time series analysis on a selection of objects (both AGN and XRBs) that have extensive, multi-decade light curves
  - **Goal**: determine characteristics present in these light curves that might correlate to importance of radiation
- Long-term:
  - Compare simulation results and real data, perform time series and statistical analyses on both



Rotational velocity at each radius at the final time step; remains Keplerian throughout simulation, as expected for a physical system



Simulated light curve: successfully distinguishes variations in flux; Inset: EXOSAT observations in the 2-20 keV energy range (X-ray) of Cygnus X-1