Warped accretion discs and spin alignment during SMBH mergers

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SMBH mergers and role of BH spin

• In standard cosmologies, galaxies undergo several mergers

• Likely formation of SMBH binaries (Komossa et al 2003)

• Lack of strong evidence for SMBH binaries
  ---> Fast evolution of binary black holes to merger

• Role of gaseous disc crucial in
  
  • a) Bringing the binary to coalescence
      (Lodato, Nayakshin, King and Pringle , 2008)
  
  • b) Determining the spin evolution of the binary components (Bogdanovic, Reynolds and Miller 2007)
SMBH mergers and role of BH spin

- The spin orientation and magnitude at coalescence is essential in determining several properties

  - Shape of the GW waveform (if and when GW detectors will fly)

  - If: (a) spin magnitude $a$ is large and (b) spins are significantly misaligned --- asymmetric GW emission --- superkick configuration (with recoil velocities up to 4000 km/sec, Campanelli et al 2007)

  - Recoiling black holes rarely observed (Civano et al 2012)

  - A recoiled BH is removed from gas-rich nuclear region --- Effects on BH growth
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L. Blecha's talk
Spin evolution in gaseous environments

- **Bogdanovic, Reynolds and Miller (2007)**: in gas rich mergers, the two BH spin likely end up aligned (alignment time much shorter than merger time \( t_{\text{merge}} \sim 10^7 \) yrs; Dotti et al 2009, Escala et al 2005)

- **Fundamental assumption**: only need each black hole to align with its own disc! (Might be very optimistic if the circumbinary disc plane is not stable, see Nixon et al. 2011, Nixon et al. 2013)
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Spin evolution in gaseous environments

- Consider a single BH and its accretion disc

- Lense-Thirring precession in the disc induces a warp (the Bardeen-Petterson effect) (Bardeen and Petterson 1975, Scheuer and Feiler 1996, Lodato and Pringle 2006)

- Inner disc align with BH, out to $R_{BP}$

- Location of $R_{BP}$: precession timescale equals warp propagation timescale

  \[ \Omega_{LT}^{-1} = t_{\nu_2} \]

- On longer timescale, BH spin aligns (or counter-aligns, see King et al 2005) with disc (Natarajan and Pringle 1998)

  \[ t_{\text{align}} \approx 7 \times 10^6 \left( \frac{a}{\alpha_2} \right)^{2/3} \left( \frac{\alpha}{0.1} \right) \left( \frac{H/R}{0.01} \right)^{2/3} \left( \frac{\dot{M}}{0.1 M_{\text{Edd}}} \right)^{-1} \left( \frac{\epsilon}{0.1} \right) \text{ yr} \]
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How fast do warps propagate in accretion discs?

• Several theories have been developed for warp propagation in discs

• Papaloizou and Pringle (1983) estimate $\alpha_2 \sim 1/2 \alpha$, for small warps and small viscosity

• Ogilvie (1999) provides a fully non-linear theory of warp propagation

  • For large warps, the warp diffusion coefficient is severely reduced (longer diffusion time-scale)
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\[
\psi = \frac{d\beta}{d \ln R}
\]

Ogilvie 1999

$\psi = 10^{-4}$

$\psi = 0.2$

$\psi = 0.5$

$\psi = 1$

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[Graphs and diagrams related to warp propagation in accretion discs]
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- Bogdanovic et al: assume the small warp value

- Perego et al: artificially reduce $\alpha_2$ by a factor up to 3 (following the numerical results of Lodato and Pringle 2007) ---＞ Still no dependence on the warp amplitude
Our approach

- As in previous works, only study the alignment of a single BH with its own disc

- Assume that the disc inclination varies on the scale R (no sharp warp): $\psi \approx \theta$
  - A more complete analysis would require a self-consistent calculation of the disc shape

- For low viscosities, the disc may break (Nixon et al, Lodato and Price, Larwood and Papaloizou): assume no alignment in this case

- All above assumptions tend to **favour alignment** (very optimistic)

- Now, alignment time does depend on the initial misalignment $\theta$
Results for constant Eddington ratio

• Perform Monte Carlo simulation varying the initial misalignment

• Given $\alpha$ (viscosity parameter), $a$ (spin parameter) and $f_{\text{Edd}} = \frac{\dot{M}}{\dot{M}_{\text{Edd}}}$ we compute the alignment time

Here assume $f_{\text{Edd}}=0.1$, $a=1$

Perego et al: $t_{\text{align}} \sim 10$ Myr

When dependence on misalignment included, the timescale becomes longer by up to an order of magnitude

Alignment would seem unlikely in this case for a large fraction (~50%) of the cases
Varying the Eddington ratio

- Here we also Monte Carlo over the Eddington ratio $f_{\text{Edd}}$ in $[10^{-4}, 1]$

- In the fully non-linear case, much weaker dependence on $\alpha$

- Highly spinning black holes highly unlikely to align within a merger time

- If $a > 0.4$, BH keep misalignment in more than 40% of the times
Varying the Eddington ratio

- Here we also Monte Carlo over the Eddington ratio $f_{\text{Edd}}$ in $[10^{-4}, 1]$

- Even if we assume a longer merger timescale, e.g. 50 Myr, most of highly spinning black holes still do not have time to align their spins

\[
\alpha_2 \approx 1/2 \alpha
\]

\[
\alpha_2 = \alpha_2(\alpha, \theta)
\]
Conclusions/Predictions

• Highly spinning BH do not align during mergers, even assuming conditions that favour alignment throughout:
  • Assume individual discs to be aligned with each other in a binary system (Nixon et al, 2011, 2013)
  • Assume warp to be smooth
• If misalignment inevitable, the lack of evidence for strong recoils implies that on average, the BH spin must be small ($a<0.4$)
  • In line with chaotic accretion picture (King and Pringle 2005)
  • Soltan argument

To do list

• Compute self-consistent shape of the disc (a la Scheuer and Feiler) for the non-linear case
• Strong assumption here: simple proxy of $10^7$ yr for the merger time
  • Need to include dependence on system parameters (i.e. $f_{Edd}$)