Jet flares as beacons for gravitational waves

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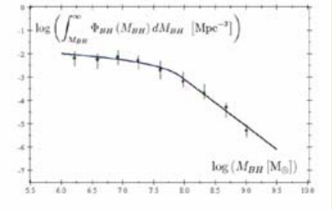
Typical mass ratios in SMBH mergers

➢ The mass distribution $\Phi_{BH}(m)$ of the galactic central SMBHs in the mass range $10^6 \div 3\times10^9$ solar masses ($M_\odot$) well described by a broken powerlaw [1]-[3] (confirmed by observational surveys [4]-[5])

➢ Break at about $10^8 M_\odot$, $\Phi_{BH}(m) \sim m^{-k}$ with $k \in (1,2)$ below and $\Phi_{BH}(m) \sim m^{-h}$ with $h \geq 3$ above [3]. The fit gives [6]:



breakpoint at $m_* = 10^{7.95} M_\odot \approx 8.9 \times 10^7 M_\odot$

➢ The probability for a specific mass ratio for SMBH encounters was estimated in [6]-[7]

- by adopting the lower values of the exponents
- as an integral over the black hole mass distribution, folded with the rate F to merge
- F scales with the capture cross section S (the dependence on the relative velocity of the two galaxies was neglected, as the universe is not old enough for mass segregation)
- $S \sim \nu^{-1/2}$ (with $\nu = m_2/m_1 \leq 1$ the mass ratio) motivated by
  - ❖ an increase with a factor of 10 in radius (10^2 in cross-section) accounts for an increase with a factor of 10^4 in mass for galaxies (comparing our Galaxy with dwarf spheroidals [8]-[9]
  - ❖ the well established correlation between the SMBH mass and the mass of the host bulge [10]
  - ❖ the mass of the central SMBH scales with both the spheroidal galaxy mass component and the total, dark matter dominated mass of a galaxy [11]
  - → the most likely mass ratio in the range $\nu \in (1/30, 1/3)$
  - → a typical value would be $\nu = 0.1$

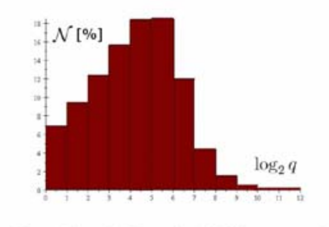


FIG. 2: (Color online) The number of SMBH encounters with mass ratios q as function of $\log_2 q$.

Consequence 1: Typical final spin in LISA sources [6]

$$\chi_f = \frac{\nu}{(1+\nu)^2}\left[4 + 4\sum_{i=1,2} \nu^{2i-3}\chi_i \cos\kappa_i + \sum_{i=1,2}\left(\nu^{2i-3}\chi_i\right)^2 + 2\chi_1\chi_2\cos\gamma\right]^{1/2}$$

➢ derived from PN arguments (for unequal masses matches well the numerical formula of [12])

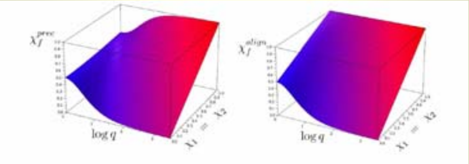
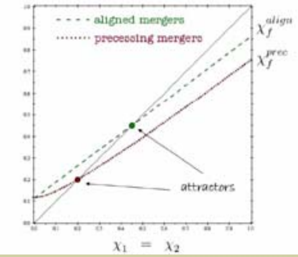


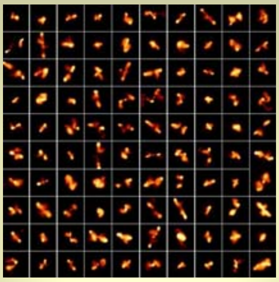
FIG. 3: (Color online) The typical final spin in supermassive black hole mergers as function of $\chi_1 = \chi_2$ and $\log q$, represented for precessing mergers (averaged over random configurations) - left panel; and mergers with the spins and orbital angular momentum fully aligned - right panel.

➢ integral over configurations

➢ further integral over mass ratios, weighted by the mass ratio probability



Consequence 2: explaining X-shaped radio galaxies



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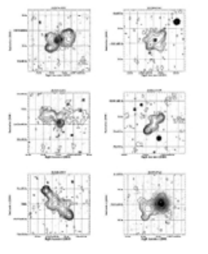


➢ X-shaped radio galaxies (XRGs) exhibit two pairs of radio lobes and jets [13]-[14]

➢ There are at least four different models for explaining XRGs, according to the recent review [15], to be chosen from case-by-case:

1. Galaxy harbouring twin AGNs
2. Back-flow diversion models
3. Rapid jet reorientation (spin-flip) models [16]
4. Jet-shell interaction model [15]

➢ The spin-flip model can explain all observations (excepting cases, when the jets are aligned with the principal axes of the host elliptical, then 4. can)

Consequence 3: Jet flares and gravitational waves

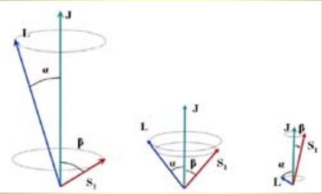
A spin-flip happens during the inspiral [7]

➢ Spin-orbit precession driven conservative and gravitational radiation driven dissipative contributions to the orbital evolution, averaged over the precession time-scale

The Evolution of the Ratio $S_1/L \approx \varepsilon^{1/2}\nu^{-1}$ in the Range $\varepsilon = 10^{-3}$–10^{-1} for Various Values of the Mass Ratio ν

$S_1/L = \varepsilon^{1/2}\nu^{-1}$	$\varepsilon \approx 10^{-3}$	$\varepsilon \approx 10^{-1}$
$\nu = 1$	0.03 ($S_1 \ll L$)	0.3 ($S_1 < L$)
$\nu = 1/3$	0.1 ($S_1 < L$)	1 ($S_1 \approx L$)
$\nu = 1/30$	1 ($S_1 \approx L$)	10 ($S_1 > L$)
$\nu = 1/900$	30 ($S_1 \gg L$)	300 ($S_1 \gg L$)

➢ the following situation applies for the typical mass ratios:



✓ Three regimes with $L > S_1$, $L \approx S_1$ and $L < S_1$, characteristic for the inspiral for the most likely mass ratios 0.3 ÷ 0.03

✓ initially the galactic BH has conserved spin → the primary jet can form

✓ the two galaxies collide → spin precession starts

✓ the spin aligns to the original **J** direction

$$\dot\alpha = -\frac{\dot L}{J}\sin\alpha > 0,$$

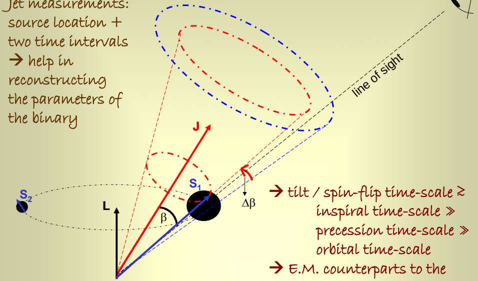
$$\dot\beta = \frac{\dot L}{J}\sin\alpha < 0.$$

→ the second jet starts to form

✓ the precessing magnetic field creates a wind, sweeping away the base of the old jet (observed)

The narrowing of the precession cone will cause variability (flares) in the jet for a limited time

Jet measurements: source location + two time intervals → help in reconstructing the parameters of the binary



→ tilt / spin-flip time-scale ≳ inspiral time-scale ≫ precession time-scale ≫ orbital time-scale

→ E.M. counterparts to the strongest GW emission likely !!!

Time intervals to be observed:

➢ precession period of S_1 :

$$T_p(\varepsilon, \nu, f_{GW}, \beta) = \frac{(1+\nu)^2}{\varepsilon\nu}\frac{\sin\beta}{\sin\kappa} f_{GW}^{-1}$$

➢ time the jet spends in Δβ :

$$T_{\Delta\beta}(\varepsilon, \nu, f_{GW}, \beta, \Delta\beta) = \frac{5\Delta\beta}{32\pi}\frac{(1+\nu)^2 \sin\kappa}{\varepsilon^3 \sin^2\beta} f_{GW}^{-1}$$

➢Their ratio:

$$\frac{T_{\Delta\beta}}{T_p}(\varepsilon, \nu, \beta; \Delta\beta) = \frac{5\Delta\beta}{32\pi}\frac{\nu\sin^2\kappa}{\varepsilon^2\sin^3\beta}$$

, where $\kappa = \alpha + \beta$, obeying

$$\kappa = \beta + \arcsin\left[\varepsilon^{1/2}\nu^{-1}\sin\beta\right]$$

For given ν and β + observed T_p and $T_{\Delta\beta}$ we can calculate $\varepsilon_{\Delta\beta}$ and f_{gw} (or m, according to $f_{GW} = \frac{c^3}{\pi G m}\varepsilon^{3/2}$).

For sources with $m = 10^6 M_\odot$, $\varepsilon_{\Delta\beta} = 0.1$, and $\nu = 0.1$ the values of T_p and $T_{\Delta\beta}$, to be observed are [17]:

β [°]	κ [°]	T_p [days]	$T_{\Delta\beta}$ [days]
20	40	116	1041
25	50	120	812
30	60	126	656
35	70	133	541
40	80	142	451

Thus 6 variables:

$(\varepsilon,\ \nu,\ \beta,\ \Delta\beta,\ f_{GW},\ \text{spin magnitude})$

and 5 measurements:

$(\Delta\beta,\ T_p,\ T_{\Delta\beta})$ $(T_{SNR10},\ T_{merger})$

Jets gravitational waves

Complementary gravitational wave measurements [18]

The leading order frequency domain waveform (for an averaged antenna pattern function):

$$\tilde h_\alpha(f) = \frac{\sqrt{3}}{2} A f^{-7/6} e^{i\psi(f)},\ \alpha = I, II$$

$$A = \frac{1}{\sqrt{30}\pi^{2/3}}\frac{m_{chirp}^{5/6}}{D_L}$$

and the LISA spectral noise density:

$$S_{h,inst}(f) = 5.049 \times 10^5 \left[a^2(f) + b^2(f) + c^2\right]$$

$$a(f) = 10^{-22.79}(f/10^{-3})^{-7/3}$$

$$b(f) = 10^{-24.54}(f/10^{-3})$$

$$c = 10^{-23.04}$$

$$S_h(f) = S_{h,inst}(f) + S_{h,conf}(f)$$

$$S_{h,conf}(f) = \begin{cases} 10^{-42.685} f^{-1.9} & f \leq 10^{-3.15} \\ 10^{-60.325} f^{-7.5} & 10^{-3.15} < f \leq 10^{-2.75} \\ 10^{-46.85} f^{-2.6} & 10^{-2.75} < f \end{cases}$$

(instrument and confusion noises [19])

gives the signal to noise ratio (SNR):

$$SNR = \sqrt{4\int_{f_{in}}^{f_{end}} \frac{\left|\tilde h(f)\right|^2}{S_h(f)} df}$$

Suppose gravitational waves are first detected following the jet flares at SNR=10, then until the merger, gives two additional time intervals. For

$\Delta\beta = 1°$, $\beta = 30°$, $T_{\Delta\beta} = 450$ days and $T_p = 80$ days

ν	m $[M_\odot]$	$\varepsilon_{\Delta\beta}$	ε_{SNR10}	T_{SNR10} [days]	T_{merger} [days]
1/3	2×10^6	0.0129	0.0138	97	332
1/10	0.5×10^6	0.0095	0.0113	457	458
1/20	0.2×10^6	0.0078	0.0139	1287	141
1/30	6768	0.0035	0.0065	1320	132

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