Supermassive black hole spin-flip during the inspiral

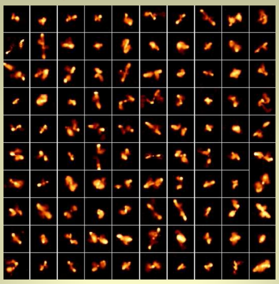
László Árpád Gergely[1], Laurentiu I. Caramete[2], Peter L. Biermann[3]
[1]University of Szeged, Hungary
[2]Institute for Space Sciences, Bucharest, Romania
[3]Max Planck Institute for Radio Astronomy, Bonn, Germany

Typical mass ratios

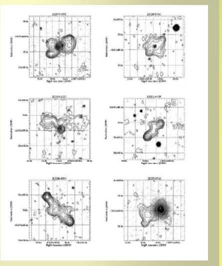
- The mass distribution $\Phi_{BH}(m)$ of the galactic central SMBHs in the mass range $3\times10^6\div3\times10^9$ solar masses ($M_\odot$) well described by a broken powerlaw [1]-[3] (confirmed by an observational survey [4])
- The break at about $10^8 M_\odot$
  - $\Phi_{BH}(m)\sim m^{-k}$ with $k\in(1,2)$, below
  - $\Phi_{BH}(m)\sim m^{-h}$ with $h\geq 3$, above [3]
- The probability for a specific mass ratio for SMBH encounters was estimated in [5]
- 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 $\nu=m_2/m_1\leq1$ 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 [6]-[7]
  - the well established correlation between the SMBH mass and the mass of the host bulge [8]
  - the mass of the central SMBH scales with both the spheroidal galaxy mass component and the total, dark matter dominated mass of a galaxy [9]

→ the most likely mass ratio in the range $\nu\in(1/30,\ 1/3)$
→ a typical value would be $\nu=0.1$

X-shaped radio galaxies



Cheung, C. C. :The Astronomical Journal, 133, 2097-2121 (2007), arXiv:astro-ph/0701278v3



- X-shaped radio galaxies (XRGs) exhibit two pairs of radio lobes and jets [10]-[11]
- There are at least four different models for explaining XRGs, according to the recent review [12], to be chosen from case-by-case:

1. Galaxy harbouring twin AGNs
2. Back-flow diversion models
3. Rapid jet reorientation (spin-flip) models [13]
4. Jet-shell interaction model [12]

- 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)

The sky in black holes

- Statistical analysis of 2,500 black hole candidates in the mass range $10^7\div10^9 M_\odot$ from a sampling volume of about 100 Mpc radius (each checked black hole candidate was a SMBH) [14] → $\Phi_{BH}(m)\sim m^{-3}$
- At masses larger then $10^9 M_\odot$ and below $10^7 M_\odot$ not enough SMBHs for statistics
- Evidence for some SMBHs in the mass range below $10^7 M_\odot$ → assume a mass function with shallower slope below $10^7 M_\odot$
- Extremely few black holes between $10 M_\odot$ and $10^6 M_\odot$ → cut-off of the mass function near the mass of the black hole in our Galactic Center, of about $3\times10^6 M_\odot$
- key difference to previous work: careful attention to have equal probability for detecting a BH in a galaxy of any Hubble type

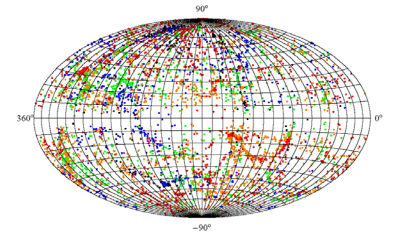


Figure 5 The sky in black holes, $\gtrsim 10^7\ M_\odot$: Aitoff projection in galactic coordinates of 5,978 candidate sources in the case of a complete sub sample (the Galactic plane remains obscured). The choice was made from a complete sample of 10,284 candidate brighter than 0.03 Jy at 2 micron, and selected at z< 0.025; this uses the 2 micron all sky survey, limited in a 20 degree band in the Galactic plane. These candidate sources are probably all black holes, with masses near to or above 10^7 solar masses; the black hole mass was determined with the black hole versus mass spheroidal stellar population correlation, and tested. The color code is Black, Blue, Green, Orange, Red corresponding to redshifts betwen 0, 0.005, 0.01, 0.015, 0.02, 0.025: Caramete et al. 2008

- discussion closely following [15]
  → typical mass ratio recovered

The spin-flip model

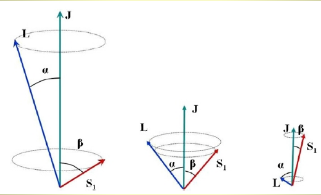
Evolution during the inspiral

- 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:



- ✓ 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

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

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

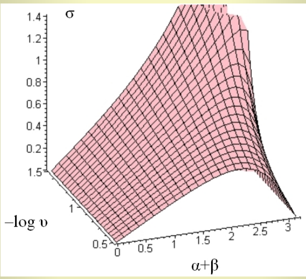
→ the second jet starts to form

- ✓ in the intermediate phase when the spin precesses, no jet formation mechanism
- ✓ the precessing magnetic field creates a wind, sweeping away the base of the old jet (observed)

Spin-flip angle distribution

In the typical mass ratio range, the spin-flip angle during the inspiral

- ✓ increases with the decrease of the mass ratio
- ✓ first increases, then decreases with the increase of the angle span by the dominant spin and orbital angular momentum
- ✓ for $\nu=0.1$ the maximum spin-flip angle of $\sigma\approx63°$ is at about $\alpha+\beta\approx160°$



Based on:

$$\boxed{\sigma = \beta_{in} - \beta_{fin} = \alpha_{fin} - \alpha_{in}\ .}$$

$$\frac{\sin 2\alpha}{1+\cos 2\alpha} \approx \frac{\sin(\alpha+\beta)}{\varepsilon^{-1/2}\nu + \cos(\alpha+\beta)}$$

with: $\varepsilon_{in} \approx 10^{-3}$ $\varepsilon_{fin} \approx 10^{-1}$
(the limits of the inspiral)

Work supported by the Polányi Program of the Hungarian National Office for Research and Technology (NKTH) and the Hungarian Scientific Research Fund (OTKA) grant 69036 (LÁG);
Contracts CNCSIS 539/2009 and CNMP 82077/2008 (LIC);
AUGER membership and theory grant 05 CU 5PD 1/2 via DESY/BMBF and VIHKOS (PLB).

Time-scales

Estimates for
- ✓ the inspiral rate $\dot{L}/L$
- ✓ angular precessional velocity Ω_p
- ✓ tilt velocity $\dot{\alpha}$ of the vectors **L** and $\mathbf{S_1}$ with respect to **J**

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

Parameter	$L > S_1$	$L \approx S_1$	$L < S_1$
$-\dot{L}/L$	$\frac{32c^3}{5Gm}\varepsilon^4\eta\ (\approx 10^{-15})$	$\frac{32c^3}{5Gm}\varepsilon^4\eta\ (\approx 10^{-11})$	$\frac{32c^3}{5Gm}\varepsilon^4\eta\ (\approx 10^{-7})$
Ω_p	$\frac{2c^3}{Gm}\varepsilon^{5/2}\eta\ (\approx 10^{-11})$	$\frac{2c^3}{Gm}\varepsilon^{5/2}\eta\frac{J}{L}\ (\approx 10^{-8}\frac{J}{L})$	$\frac{2c^3}{Gm}\varepsilon^3\ (\approx 10^{-5})$
$\frac{\dot{\alpha}}{\sin(\alpha+\beta)}$	$\frac{32c^3}{5Gm}\varepsilon^{9/2}\frac{\eta}{\nu}\ (\approx 10^{-16})$	$\frac{32c^3}{5Gm}\varepsilon^{9/2}\frac{\eta}{\nu}\frac{L^2}{J^2}\left(\approx 10^{-11}\frac{L^2}{J^2}\right)$	$\frac{32c^3}{5Gm}\varepsilon^{7/2}\eta\nu\ (\approx 10^{-8})$

Notes. The numbers in brackets represent inverse timescales in s^{-1}, calculated for the typical mass ratio $\nu = 10^{-1}$, post-Newtonian parameter 10^{-3}, 10^{-2}, and 10^{-1}, respectively, and $m = 10^8\ M_\odot$ (then $c^3/Gm = 2\times10^{-3}\ s^{-1}$).

→ tilt / spin-flip time-scale ≳ inspiral time-scale ≫ precession time-scale ≫ orbital time-scale (in all regimes)
→ the spin-flip time-scale for typical mass ratio of 0.1 is found to be only about three years
→ E.M. counterparts to the strongest GW emission likely !!!

References

[1] W. H. Press, P. Schechter, *Astrophys. J.* **187**, 425 (1974)

[2] A. S. Wilson, E. J. M. Colbert, *Astrophys. J.* **438**, 62 (1995)

[3] T. R. Lauer et al., *Astrophys. J.* **662**, 808L (2007)

[4] L. Ferrarese et al., *Astrophys. J. Suppl.* **164**, 334 (2006)

[5] L. Á. Gergely, P. L. Biermann, *Astrophys. J.* **697**, 1621 (2009)

[6] Gilmore G et al., *Nucl. Phys. B* **173**, 15 (2007)

[7] A. Klypin, H.-S. Zhao, R. S. Somerville, *Astrophys. J.* **573**, 597 (2002)

[8] J. Magorrian et al., *Astronomical J.* **115**, 2285 (1998)

[9] A. J. Benson, D. Džanović, C. S. Frenk, R. Sharples, *Mon. Not. Roy. Astron. Soc.* **379**, 841 (2007)

[10] J. P. Leahy, A. G. Williams, *Mon. Not. Royal. Astron. Soc.* **210**, 929 (1984).

[11] J. P. Leahy, R. A. Perley, *Astron. J.* **102**, 537 (1991); A. R. S. Black et al., *Mon. Not. Royal. Astron. Soc.* **256**, 186 (1992)

[12] Gopal-Krishna, P. L. Biermann, L. Á. Gergely, P. J. Wiita, in preparation (2010)

[13] Ch. Zier, P. L. Biermann, *Astron. Astroph.* **377**, 23 (2001); D. Merritt, R. Ekers, *Science* **297**, 1310 (2002); Gopal-Krishna, P. L. Biermann, P. J. Wiita, *Astrophys. J. Letters* **594**, L103 (2003); F. K. Liu, *Mon. Not. Royal. Astron. Soc.* **347**, 1357 (2004)

[14] L. I. Caramete, P. L. Biermann, submitted to *Astron. Astroph.* (2009), E-print: arXiv:0908.2764

[15] J. Silk, T. Takahashi, *Astrophys. J.* **229**, 242 (1979)