Frank M. Rieger

Supermassive binary black holes among cosmic gamma-ray sources

Abstract Supermassive binary black holes (SBBHs) are a natural outcome of galaxy mergers. Here we show that low-frequency \((f \leq 10^{-6} \text{ Hz})\) quasi-periodic variability observed from cosmic blazar sources can provide substantial inductive support for the presence of close \((d \lesssim 0.1 \text{ pc})\) SBBHs at their centers. It is argued on physical grounds that such close binary systems are likely to give rise to different (although not independent) periodicities in the radio, optical and X-ray/TeV regime, and, hence, that detection of appropriate period ratios significantly corroborates the SBBH interpretation. This is illustrated for a binary model where optical longterm periodicity is related to accretion disk interactions, radio periodicity to Newtonian jet precession, and periodicities in the high energy bands to the orbital motion of the jet. We use the observed periodicities to constrain the properties for a sample of SBBH candidates including OJ 287 and AO 0235+16, and discuss the results within the context of jet activity and binary evolution.

Keywords Supermassive binary black holes, periodicity, Active Galaxies

1 Introduction

Violent galaxy mergers are known to play a vital role in the cosmological evolution of galaxies and the growth of supermassive black holes (BHs). Since almost every bright galaxy seems to contain a black hole (BH), frequent formation of supermassive binary black holes is naturally expected to occur during cosmic time, e.g., see [1][2][3]. In cosmic bottom-up scenarios, for example, elliptical galaxies, such as the host galaxies of radio loud AGNs, are usually thought to form when two spiral galaxies collide and merge. Interacting galaxies are indeed observationally well-known and the observation that the relative number of spiral to elliptical galaxies tends to increase in distant clusters [4], gives additional credit to the underlying evolutionary picture. Moreover, direct observational evidence for formation of wide \((d \gg 1 \text{ pc})\) supermassive binary systems has been established recently based on Chandra observations of the ultraluminous infrared galaxy NGC 6240 [5] and VLBA observations of the radio galaxy 0402+379 [6]. While the existence of wide SBBHs may thus be regarded as observationally well grounded, the anticipated existence of close \((d \sim 0.01 - 1 \text{ pc})\) SBBHs appears much more ambiguous. Indeed, there is little direct observational evidence so far for a close, secondary supermassive BH in the nuclear region of Active Galaxies. On the other hand, dynamical friction and slingshot interactions with stars normally ensure that a binary system gets quickly closer, reaching separations \(d_c \sim 1 \text{ pc}\) in less than \(10^8 \text{ yr}\) [1]. As the number of field stars with ideal impact parameters decreases with \(d\), the binary evolution will then stall at around \(d_c\) (i.e., well above the separation at which gravitational radiation becomes important), unless further angular momentum can be efficiently removed by other processes such as, for example, influx of gas or accretion disk interactions. SBBH systems are thus likely to spend most of their time at separations \(d \sim (0.05 - 1) \text{ pc}\) for BH masses of order \(10^8 \text{ M}_\odot\). While the origin of X-shaped radio morphologies in some radio galaxies may provide some phenomenological evidence for a possible spin flip during the final merger stage [7], thus suggesting that at least some SBBHs may coalesce within a Hubble time, it is theoretically still not yet fully understood today whether that can be achieved by a substantial fraction of SBBHs, e.g., see [1][8][9][10][11][12][13]. As shown below, our analysis presented here provides further phenomenological support for relatively short merging timescales in AGNs.

F.M. Rieger
UCD School of Mathematical Sciences
University College Dublin, Belfield, Dublin 4, Ireland
E-mail: frank.rieger@ucd.ie
2 Periodic variability in close SBBHs

The presence of close SBBH systems has been repeatedly invoked as plausible source for a number of observational findings in blazar-type AGNs, ranging from misalignment and precession of jets to helical trajectories and quasi-periodic variability, see \[14,15\] for recent reviews. As illustration of the latter, consider a simple SBBH model with a precessing jet:

Interactions of the companion with the accretion disk around the primary BH may then naturally account for longterm optical periodicity with periods of the order of \( P_{\text{opt}} \sim \) several years as observed in a number of blazars, e.g., see \[16\] for OJ 287 and also Table \[1\], at least in those cases where the disk provides a non-vanishing contribution to the observed optical spectral flux. Accordingly, we may derive an upper limit for the intrinsic Keplerian orbital period of the binary

\[
P_{k} \leq \frac{2}{(1 + z)} P_{\text{opt}}^{\text{obs}}
\]

by assuming that the optical longterm periodicity is caused by the secondary BH crossing the disk around the primary twice per orbital period. Note, however, that due to internal disc warping and/or disc precession, some deviations from strict periodicity are likely to occur.

The detection of helical jet paths in an increasing number of blazar sources \[17,18,19,20\] suggests that quasi-periodic variability – especially in those energy bands dominated by the jet, e.g., radio, X- and γ-ray – may also naturally arise as a consequence of differential Doppler boosting \( S_{\nu}(t) = \delta(t)^{n} S'_{\nu} \) for a periodically changing viewing angle, where \( \delta(t) \) is the time-dependent Doppler factor, \( n > 3 \), and \( S'_{\nu} \) the spectral flux in the comoving frame \[21,22\]. For non-ballistic helical motion, classical travel time effects will then lead to a shortening of observable periods \( P_{\text{obs}} \) with respect to the real physical driving period \( P \) such that

\[
P_{\text{obs}} \sim (1 + z) \frac{P}{\gamma_{b}^{2}}
\]

where \( \gamma_{b} \approx (5 - 15) \) is the typical bulk flow Lorentz factor \[20\]. Orbital motion and (Newtonian) disk precession caused by tidally induced perturbations in the disk \[23,24\] belong to the most obvious driving sources for helical jet paths. If, as it is usually believed, the high energy emission is produced on small jet scales, it may be primarily modulated by the orbital SBBH motion, suggesting observable periods

\[
P_{\text{obs}} \sim 30 \left( \frac{P_{\text{obs}}}{10 \text{yr}} \right)^{2} \frac{15}{\gamma_{b}} \text{ d}.
\]

as indeed observed [cf. Table \[1\]]. On the other hand, simple cooling arguments suggest that a significant part of the radio emission may originate on larger scales, where Newtonian jet precession can no longer be neglected. In general, the driving period for Newtonian jet precession is (at least) an order of magnitude higher than the orbital period \( P_{k} \), i.e., \( P = P_{\nu} \geq 10 P_{k} \) \[20\], so that observable radio periods are expected to satisfy

\[
P_{\text{obs}}^{\text{radio}} \geq 20 P_{\text{obs}}^{\text{opt}} / \gamma_{b}^{2}.
\]

Note, that if \( P_{\nu} \) is rather small (say \( P_{\nu} \sim 10 P_{k} \)), moderate bulk Lorentz factors are still sufficient to account for \( P_{\text{obs}}^{\text{radio}} < P_{\text{obs}}^{\text{opt}} \) as sometimes observed, cf. Table \[1\]. Let us note, that a close SBBH interpretation for the origin of (some) quasi-periodic variability is certainly not the only possible explanation, as other (not mutually exclusive!) origins (e.g., disk instabilities, orbiting disk hot spots) are conceivable as well. What makes the SBBH interpretation unique, however, is that it seems to allow corroboration of facts otherwise not possible:

(1.) It is based on quite general arguments for (bottom-up) structure formation (galaxy mergers), (2.) it naturally accounts for helical jet trajectories observed in many sources, (3.) it can offer a reasonable solution to the problem of divergent central mass estimates derived from high energy emission models and host galaxy observations \[25\], and (4.) it provides a coherent explanation for longterm periodic variability. In particular, as shown above, strong support can be provided by the detection of quasi-periodic variability on different timescales in different energy bands.

3 Application to individual sources

3.1 AO 0235+16:

Long-term monitoring (1975-2000) of this well-known and highly variable BL Lac object has shown evidence for a \( (5.7 \pm 0.5) \) yr radio and a possible \( (2.95 \pm 0.15) \) or \( (5.7 \pm 0.5) \) yr optical periodicity \[20,27\]. Both findings have been interpreted within a close SBBH framework \[25,29\], cf. \[30\] for a discussion. However, during the latest radio to optical monitoring campaign in 2003-2005, no evidence for a major radio or optical outburst – extrapolated from previous observational results to occur within the campaign – was found \[31,32\]. While the non-detection of a major radio outburst might be relatively easy accommodated in a precession-driven helical jet model \[28\] by taking, for example, a moderate change of the jet bulk Lorentz or Doppler factor (decrease) and/or the inner disk properties during an active stage fully into account, the non-detection of the expected optical outburst (if indeed associated with accretion disk interactions, e.g., \[28\]), is somewhat more challenging for a consistent SBBH interpretation. A possible way out – apart from the possibility of inaccurate previous periodicity results, i.e., the real optical period may actually be \( \sim 8 \) yr \[32\], which needs to be checked in detail – is to assume that, similar to the accretion-ejection connection in microquasars, an active (low-hard-type) source stage may be associated with enhanced intrinsic (!) jet activity and a decrease in optical disk flux,
Table 1 Properties of a sample of blazar SBBH candidates, cf. Rieger et al., in preparation for more details, with masses in $10^8 M_\odot$, and upper limits for the associated binary lifetime $\tau_{\text{grav}}$ due to gravitational radiation in units of $10^8$ yr for typical mass ratios $\geq 0.01$. References given are for observed periods $P_{\text{obs}}$ identified.

| name   | redshift $z$ | periods $P_{\text{obs}}$ | Ref. | $(m + M)$ | $P_k$ [yr] | $d/10^{21} \text{cm}$ | $\tau_{\text{grav}}$ |
|--------|--------------|--------------------------|------|-----------|-------------|------------------------|----------------------|
| Mkn 501| 0.034        | $23.6 \text{ d (X-ray)}$ | 43   | (2-7)     | (6-14)      | (2.5-6)                | 5.30                 |
|        |              | $\sim 23 \text{ d (TeV)}$| 44   |           |             |                        |                      |
| BL Lac | 0.069        | $13.97 \text{ yr (optical)}$| 35   | (2-4)     | (13-26.1)   | (4.8-9.7)              | 28.9                 |
|        |              | $\sim 4 \text{ yr (radio)}$ | 45   |           |             |                        |                      |
| ON 231 | 0.102        | $\sim 13.6 \text{ yr (optical)}$ | 46   | $\geq 1$ | (12.3-24.7) | $\geq 3.7$         | 79.4                 |
|        |              | $\sim 3.8 \text{ yr (optical)}$ | 47   |           |             |                        |                      |
| 3C 273 | 0.158        | $13.65 \text{ yr (optical)}$ | 48   | (6-10)   | (11.8-23.6) | (6.5-12.3)             | 3.55                 |
|        |              | $5.55 \text{ yr (radio)}$ | 49   |           |             |                        |                      |
| OJ 287 | 0.306        | $11.86 \text{ yr (optical)}$ | 50   | 6.2       | (9.1-18.2)  | (5.5-8.8)              | 1.68                 |
|        |              | $\sim 12 \text{ yr (infrared)}$ | 51   |           |             |                        |                      |
|        |              | $\sim 1.66 \text{ yr (radio)}$ | 52   |           |             |                        |                      |
|        |              | $\sim 40 \text{ d (optical)}$ | 53   |           |             |                        |                      |
| 3C 66A | 0.444        | $4.52 \text{ yr (optical)}$ | 27   | $\geq 1$ | (3.1-6.3)   | $\geq 1.5$            | 2.08                 |
|        |              | $65 \text{ d (optical)}$ | 54   |           |             |                        |                      |
| AO 0235| 0.940        | $2.95 \text{ yr (optical)}$ | 27   | $\geq 1$ | (1.5-3.1)   | $\geq 0.95$           | 0.31                 |
|        |              | $8.2 \text{ yr (optical)}$ | 52   | (4.2-8.4) | $\geq 1.81$ | 4.48                  |                      |
|        |              | $5.7 \text{ yr (radio)}$ | 26   |           |             |                        |                      |
| 3C 446 | 1.404        | $4.7 \text{ yr (optical)}$ | 52   | 6.5       | (1.9-3.9)   | (2.0-3.2)             | 0.03                 |
|        |              | $5.8 \text{ yr (radio)}$ | 53   |           |             |                        |                      |

so that the corresponding disk contribution might be swamped by emission from the jet. If this is the case, then one might expect some orbital-driven optical variability [cf. eq. (4)] to occur on timescales $\geq 20 \text{ d}$ assuming $\gamma_{b, \text{optical}} \simeq 8$ for the optical regime [35]. Clearly, extensive multiwavelength monitoring of this source around the next SBBH anticipated outburst and advanced analysis methods will be important to clarify whether the latest anomaly may turn into a falsification of a simple SBBH scenario, where optical longterm periodicity is related to disk crossing. We note that circumstantial evidence for very high Doppler factors $\sim 100$ ($\gamma_{b} \geq 50$) in AO 0235 have been reported in the literature, e.g., see [34], which – if indeed true – would also allow for some orbital-driven intraday variability. A very interesting alternative explanation for the origin of some radio QPOs in AO 0235+16 (including its $\sim 5.7 \text{ yr periodicity}$) has been proposed recently [35], suggesting that they might be related to periodic plasma injection into the jet driven by the p-mode oscillation of a thick inner disk (probably excited by a close SBBH) with a relatively high transition radius $R_{\text{tr}} \sim 10^8 r_g$ (cf. however also the general arguments for much smaller transition radii in BL Lacs, [36]) and associated intrinsic fundamental frequency $f_0 \simeq 0.18 \text{ yr}^{-1} (R_{\text{tr}}/1.2 \cdot 10^8 r_g)^{-3/2} (4.7 \cdot 10^8 M_\odot/M_{\text{BH}})$. As the QPOs are thought to arise due to periodic plasma injection, the model seems to imply that similar QPOs should be observable in different jet-dominated energy bands (i.e, not only in the radio), which may allow a straightforward test. To complicate matters, note however that due to the above noted travel-time effects the observed radio periods may not necessarily correspond to the intrinsic driving periods.

3.2 OJ 287:

Optical and infrared monitoring of this famous BL Lac object have shown strong evidence for a $\sim 12 \text{ yr}$ [37] longterm, and a possible $\sim 40 \text{ d}$ midterm periodicity [39], with the 12 yr periodicity commonly interpreted as due to a close SBBH system, e.g., see [37,16,40]. Assuming the 12 yr QPO to be caused by disk crossing implies $P_k \lesssim 18.2 \text{ yr}$. Interestingly, orbital-driven helical jet motion [Eq. (3)] then suggests observable midterm periodicity $P_{\text{obs}} \lesssim 50 \text{ d}$ for $\gamma_{b} \sim 13$ as derived from SED multiwavelength modelling of OJ 287 [11], which is well consistent with the observed timescale. If the radio emission emerges from larger Newtonian-precession-modulated scales with $P_p \sim 10 P_k$, radio QPOs with $P_{\text{obs}} \sim 1.5 \text{ yr}$ might be expected assuming a similar bulk Lorentz factor for the radio regime. Again, there is significant evidence for such a periodicity in the radio data [12], suggesting that a close SBBH may indeed offer a powerful explanatory framework.

4 Jet activity and evolution of SBBHs

Table [11] presents properties derived for a sample of blazar SBBH candidates, where the observed periodicities have been used to estimate the last three columns: In all cases the gravitational lifetime of the binary is (a) significantly smaller than the Hubble time for the most likely range of mass ratios, a result that gives strong phenomenological support to the notion that SBBHs can indeed coalesce, and (b) still large enough to satisfy the minimum source lifetime required for jet fuelling (e.g., $\tau \sim 10^6 \text{ yr}$ for the quasar 3C 273). The derived separa-
tions $d$ are of order of the maximum size $r_d \sim 1000 r_g$ (as given by the Toomre stability condition $Q \simeq 1$) for a standard Shakura & Sunyaev disk around the primary. Accordingly, our results suggest that the candidate sources may undergo early stages of binary-disk interaction, where the orbit of the secondary BH is still inclined with respect to the circumprimary disc [55]. This may qualify our assumption that the secondary BH indeed hits the disk around the primary twice per orbital period, so that the larger (upper bound) values for $P_k$ and $d$ in Table 1 appear to be more realistic. Accretion disk interactions will lead to an accelerated evolution of the binary and can also excite the binary to eccentricities $e \sim 0.1$ [55,12]. Gas accretion and binary-disc interactions are thus very likely to dominate the most critical binary evolution stage between $d \sim 0.01 - 1$ pc, supporting the notion that SBBH systems are important but temporary feature of galaxy evolution, e.g., [9]. Binary-disc interactions can also provide a natural trigger for enhanced jet activity (e.g., time-dependent increase of accretion rate, cf. [37]) and may even lead to recurrent ejection of superluminal jet components. Moreover, during collision the disk gas will be perturbed, shocked, heated and ejected at the point of collision, which may lead to the possible formation of hot, optically thick outflows from the disk with maximum luminosity up to the Eddington limit of the secondary [56].

5 Conclusion

While each piece of observational evidence (e.g., helical jet trajectories, periodic variability etc.) may in principle allow a variety of alternative interpretations, we believe (cf. §2) that a strong cumulative (phenomenology-based) case can be built for the presence of close supermassive binary black holes at the centers of (at least some) radio-loud Active Galaxies. If so, then simple AGN unification schemes may be fundamentally incomplete as, for example, activity cycles, jet structure and emission properties may be strongly affected by the presence of a secondary BH. Longterm monitoring of blazar sources, the use of astronomical plate archives and sophisticated analysis methods may thus be crucial for further in-depth assessment of the robustness of the observational base.

Acknowledgements Partial support by a Cosmogrid Fellowship and useful comments by the referee are gratefully acknowledged.

References

1. Begelman, M.C., Blandford, R.D., Rees, M.J.: Nature 287, 307 (1980)

2. Ferrarese, L., Ford, H.: SSrv 116, 523 (2005)

3. Lobanov, A.P.: Mem. S.A.I. 76, 164 (2005)

4. Dressler, A. et al.: ApJ 490, 577 (1997)

5. Komossa, S., et al.: ApJL 582, L15 (2003)

6. Rodriguez, C., et al.: ApJ 646, 49 (2006)

7. Merritt, D., Ekers, R. D.: 2002, Science 297, 1310 (2002)

8. Quinlan, G. D., Hernquist, L.: New Astronomy 2, 533 (1997)

9. Gould, A., Rix, H.-W.: ApJL 532, L29 (2000)

10. Yu, Q.: MNRAS 331, 935 (2002)

11. Chattjee, P., et al.: ApJ 592, 32 (2003)

12. Armitage, P.J., Natarajan, P.: ApJ 634, 921 (2005)

13. Merritt, D., Milosavljevic, M.: Living Reviews in Relativity 8 (2005)

14. Rieger, F.M.: in Proc. 22nd Texas Symposium on Relativistic Astrophysics (Stanford 2004), eds. P. Chen et al. (eConf:C041213), 1601 (2005a)

15. Komossa, S.: Mem. S.A.R. 77, 733 (2006)

16. Valtorta, E., et al.: ApJ 531, 744 (2000)

17. Zensus, A.: ARA&A 35, 607 (1997)

18. Rantakyrö, F.T., et al.: A&A 341, 451 (1998)

19. Kellermann, K.I., et al.: ApJ 609, 539 (2004)

20. Rieger, F.M.: ApJL 615, L5 (2004)

21. Rieger, F.M., Mannheim, K.: A&A 359, 948 (2000)

22. De Paolis, F., et al.: A&A 388, 470 (2002)

23. Katz, J.: ApJ 478, 527 (1997)

24. Romero, G., et al.: A&A 360, 57 (2000)

25. Rieger, F.M., Mannheim, K.: A&A 397, 121 (2003)

26. Raiteri, C.M., et al.: A&A 377, 396 (2001)

27. Fan, J.H., et al.: A&A 381, 1 (2002)

28. Romero, G.E., Fan, J., & Nuza, S.E.: ChJAA 3, 513 (2003)

29. Ostorero, L., Villata, M., Raiteri, C.M.: A&A 419, 913 (2004)

30. Rieger, F.M.: AIP Conf. Proc. 745, 487 (2005b)

31. Raiteri, C.M., et al.: A&A 438, 39 (2005)

32. Raiteri, C.M., et al.: A&A 459, 731 (2006)

33. Zhang, L.Z., Fan, J.H., Cheng, K.S.: PASJ 54, 159 (2002)

34. Frey, S., et al.: PASJ 58, 217 (2006)

35. Liu, F.K., Zhao, G., Wu, X-B.: ApJ 650, 749 (2006)

36. Cao, X.: ApJ 599, 147 (2003)

37. Sillanpää, A., et al.: ApJ 325, 628 (1988)

38. Fan, J.H., et al.: ApJ 573, 173 (1999b)

39. Wu, J., et al.: AJ 132, 1256 (2006)

40. Liu, F.K., Wu, X-B.: A&A 388, L45 (2002)

41. Padovani, P., et al.: MNRAS 328, 931 (2001)

42. Hughes, P. A., Aller, H. D., Aller, M. F.: ApJ 503, 662 (1998)

43. Kranich, D., et al.: 26th ICRC (Salt Lake City) 3, 358 (1999)

44. Osone, S: Astroparticle Physics 26, 209 (2006)

45. Kelly, B.C., et al.: ApJ 591, 695 (2003)

46. Liu, F.K., Xie, G.Z., Bai, J.M.: A&A 295, 1 (2004)

47. Belokon, E.T., Babadzhanyants, M.K., Pollock, J.T.: A&A 356, L21 (2000)

48. Fan, J.H., Romero, G.E., Lin, R.: ChA&A 25, 282 (2001)

49. Ciaramella, A., et al.: A&A 419, 485 (2004)

50. Fan, J.H., et al.: A&A 333, 163 (1999a)

51. Linelna, M., et al.: ApJ 521, 561 (1999)

52. Webb, J.R., et al.: AJ 95, 374 (1988)

53. Kudryavtseva, N.A., Pyatunina, T.B.: Astronomy Reports 50, 1 (2006)

54. Goodman, J.: MNRAS 339, 937 (2003)

55. Ivanov, P.B., Papaloizou, J.C.B., Poharev, A.G.: MNRAS 307, 79 (1999)

56. Ivanov, P.B., Igumenshchev, I.V., Novikov, I.D.: ApJ 507, 131 (1998)