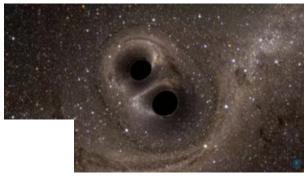# Binary black hole

A **binary black hole** (**BBH**) is a system consisting of two black holes in close orbit around each other. Like black holes themselves, binary black holes are often divided into stellar binary black holes, formed either as remnants of high-mass binary star systems or by dynamic processes and mutual capture, and binary supermassive black holes believed to be a result of galactic mergers.

For many years, proving the existence of binary black holes was made difficult because of the nature of black holes themselves, and the limited means of detection available. However, in the event that a pair of black holes were to merge, an immense amount of energy should be given off as gravitational waves, with distinctive waveforms that can be calculated using general relativity.[2][3][4] Therefore, during the late 20th and early 21st century, binary black holes became of great interest scientifically as a potential source of such waves,

Computer simulation of the black hole binary system GW150914 as seen by a nearby observer, during its final inspiral, merge, and ringdown. The star field behind the black holes is being heavily distorted and appears to rotate and move, due to extreme gravitational lensing, as space-time itself is distorted and dragged around by the rotating black holes.[1]

and a means by which gravitational waves could be proven to exist. Binary black hole mergers would be one of the strongest known sources of gravitational waves in the Universe, and thus offer a good chance of directly detecting such waves. As the orbiting black holes give off these waves, the orbit decays, and the orbital period decreases. This stage is called binary black hole inspiral. The black holes will merge once they are close enough. Once merged, the single hole settles down to a stable form, via a stage called ringdown, where any distortion in the shape is dissipated as more gravitational waves.[5] In the final fraction of a second the black holes can reach extremely high velocity, and the gravitational wave amplitude reaches its peak.

The existence of stellar-mass binary black holes (and gravitational waves themselves) was finally confirmed when LIGO detected GW150914 (detected September 2015, announced February 2016), a distinctive gravitational wave signature of two merging stellar-mass black holes of around 30 solar masses each, occurring about 1.3 billion light years away. In its final 20 ms of spiraling inward and merging, GW150914 released around 3 solar masses as gravitational energy, peaking at a rate of 3.6×10^{49} watts — more than the combined power of all light radiated by all the stars in the observable universe put together.[6][7][8] Supermassive binary black hole candidates have been found, but not yet categorically proven.[9]

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Occurrence

Supermassive black-hole binaries are believed to form during galaxy mergers. Some likely candidates for binary black holes are galaxies with double cores still far apart. An example double nucleus is NGC 6240.[10] Much closer black-hole binaries are likely in single core galaxies with double emission lines. Examples include SDSS J104807.74+005543.5[11] and EGSD2 J142033.66 525917.5.[10] Other galactic nuclei have periodic emissions suggesting large objects orbiting a central black hole, for example in OJ287.[12]

Measurements of the peculiar velocity of the mobile SMBH in the galaxy J0437+2456 indicate that it is a promising candidate for hosting either a recoiling or binary SMBH, or an ongoing galaxy merger.[13]

The quasar PG 1302-102 appears to have a binary black hole with an orbital period of 1900 days.[14]

Stellar mass binary black holes have been demonstrated to exist, by the first detection of a black hole merger event GW150914 by LIGO.[15]

Final parsec problem

When two galaxies collide, the supermassive black holes at their centers are very unlikely to hit head-on, and would in fact most likely shoot past each other on hyperbolic trajectories if some mechanism did not bring them together. The most important mechanism is dynamical friction, which transfers kinetic energy from the black holes to nearby matter. As a black hole passes a star, the gravitational slingshot accelerates the star while decelerating the black hole.

This slows the black holes enough that they form a bound, binary, system, and further dynamical friction steals orbital energy from the pair until they are orbiting within a few parsecs of each other. However, this process also ejects matter from the orbital path, and as the orbits shrink, the volume of space the black holes pass through reduces, until there is so little matter remaining that it could not cause merger within the age of the universe.

Gravitational waves can cause significant loss of orbital energy, but not until the separation shrinks to a much smaller value, roughly 0.01–0.001 parsec.

Nonetheless, supermassive black holes appear to have merged, and what appears to be a pair in this intermediate range has been observed, in PKS 1302-102.[16][17] The question of how this happens is the "final parsec problem".[18]

A number of solutions to the final parsec problem have been proposed. Most involve mechanisms to bring additional matter, either stars or gas, close enough to the binary pair to extract energy from the binary and cause it to shrink. If enough stars pass close by to the orbiting pair, their gravitational ejection can bring the two black holes together in an astronomically plausible time.[19]

One mechanism that is known to work, although infrequently, is a third supermassive black hole from a second galactic collision.[20] With three black holes in close proximity, the orbits are chaotic and allow three additional energy loss mechanisms:

1. The black holes orbit through a substantially larger volume of the galaxy, interacting with (and losing energy to) a much greater amount of matter,
2. The orbits can become highly eccentric, allowing energy loss by gravitational radiation at the point of closest approach, and
3. Two of the black holes can transfer energy to the third, possibly ejecting it.[21]

Lifecycle

Inspiral

The first stage of the life of a binary black hole is the *inspiral*, a gradually shrinking orbit. The first stages of the inspiral take a very long time, as the gravitation waves emitted are very weak when the black holes are distant from each other. In addition to the orbit shrinking due to the emission of gravitational waves, extra angular momentum may be lost due to interactions with other matter present, such as other stars.

As the black holes' orbit shrinks, the speed increases, and gravitational wave emission increases. When the black holes are close the gravitational waves cause the orbit to shrink rapidly.

The last stable orbit or innermost stable circular orbit (ISCO) is the innermost complete orbit before the transition from inspiral to *merger*.

Merger

This is followed by a plunging orbit in which the two black holes meet, followed by the merger. Gravitational wave emission peaks at this time.

Ringdown

Immediately following the merger, the now single black hole will "ring". This ringing is damped in the next stage, called the *ringdown*, by the emission of gravitational waves. The ringdown phase starts when the black holes approach each other within the photon sphere. In this region most of the emitted gravitational waves go towards the event horizon, and the amplitude of those escaping reduces. Remotely detected gravitational waves have a fast reducing oscillation, as echos of the merger event result from tighter and tighter spirals around the resulting black hole.

Observation

The first observation of stellar mass binary black holes merging, GW150914, was performed by the LIGO detector.[15][22][23] As observed from Earth, a pair of black holes with estimated masses around 36 and 29 times that of the Sun spun into each other and merged to form a 62 solar mass black hole (approximate) on 14 September 2015, at 09:50 UTC.[24] Three solar masses were converted to gravitational radiation in the final fraction of a second, with a peak power 3.6×10^{56} ergs/second (200 solar masses per second),[15] which is 50 times the total output power of all the stars in the observable universe.[25] The merger took place $440\,^{+160}_{-180}$ megaparsecs from Earth,[26] between 600 million and 1.8 billion years ago.[22] The observed signal is consistent with the predictions of numerical relativity.[2][3][4]

Dynamics modelling

Some simplified algebraic models can be used for the case where the black holes are far apart, during the *inspiral* stage, and also to solve for the final *ringdown*.

Post-Newtonian approximations can be used for the inspiral. These approximate the general relativity field equations adding extra terms to equations in Newtonian gravity. Orders used in these calculations may be termed 2PN (second order post Newtonian) 2.5PN or 3PN (third order post Newtonian). Effective-one-body (EOB) solves the dynamics of the binary black hole system by transforming the equations to those of a single object. This is especially useful where mass ratios are large, such as a stellar mass black hole merging with a galactic core black hole, but can also be used for equal mass systems.

For the ringdown, black hole perturbation theory can be used. The final Kerr black hole is distorted, and the spectrum of frequencies it produces can be calculated.

To solve for the entire evolution, including merger, requires solving the full equations of general relativity. This can be done in numerical relativity simulations. Numerical relativity models space-time and simulates its change over time. In these calculations it is important to have enough fine detail close into the black holes, and yet have enough volume to determine the gravitation radiation that propagates to infinity. In order to make this have few enough points to be tractable to calculation in a reasonable time, special coordinate systems can be used such as Boyer-Lindquist coordinates or fish-eye coordinates.

Numerical relativity techniques steadily improved from the initial attempts in the 1960s and 1970s.[27][28] Long-term simulations of orbiting black holes, however, were not possible until three groups independently developed groundbreaking new methods to model the inspiral, merger, and ringdown of binary black holes [2][3][4] in 2005.

In the full calculations of an entire merger, several of the above methods can be used together. It is then important to fit the different pieces of the model that were worked out using different algorithms. The Lazarus Project linked the parts on a spacelike hypersurface at the time of the merger.[29]

Results from the calculations can include the binding energy. In a stable orbit the binding energy is a local minimum relative to parameter perturbation. At the innermost stable circular orbit the local minimum becomes an inflection point.

The gravitational waveform produced is important for observation prediction and confirmation. When inspiralling reaches the strong zone of the gravitational field, the waves scatter within the zone producing what is called the post Newtonian tail (PN tail).[29]

In the ringdown phase of a Kerr black hole, frame-dragging produces a gravitation wave with the horizon frequency. In contrast the Schwarzschild black-hole ringdown looks like the scattered wave from the late inspiral, but with no direct wave.[29]

The radiation reaction force can be calculated by Padé resummation of gravitational wave flux. A technique to establish the radiation is the Cauchy characteristic extraction technique CCE which gives a close estimate of the flux at infinity, without having to calculate at larger and larger finite distances.

The final mass of the resultant black hole depends on the definition of mass in general relativity. The Bondi mass M_B is calculated from the Bondi-Sach mass loss formula. $\frac{dM_B}{dU} = -f(U)$. With f(U) the gravitational wave flux at retarded time U. f is a surface integral of the News function at null infinity varied by solid angle. The Arnowitt-Deser-Misner (ADM) energy or ADM mass is the mass as measured at infinite distance and includes all the gravitational radiation emitted. $M_{ADM} = M_B(U) + \int_{-\infty}^{U} F(V)dV$.

Angular momentum is also lost in the gravitational radiation. This is primarily in the z axis of the initial orbit. It is calculated by integrating the product of the multipolar metric waveform with the news function complement over retarded time.[30]

Shape

One of the problems to solve is the shape or topology of the event horizon during a black-hole merger.

In numerical models, test geodesics are inserted to see if they encounter an event horizon. As two black holes approach each other, a 'duckbill' shape protrudes from each of the two event horizons towards the other one. This protrusion extends longer and narrower until it meets the protrusion from the other black hole. At this point in time the event horizon has a very narrow X-shape at the meeting point. The protrusions are drawn out into a thin thread.[31] The meeting point expands to a roughly cylindrical connection called a *bridge*.[31]

Simulations as of 2011 had not produced any event horizons with toroidal topology (ring-shaped). Some researchers suggested that it would be possible if, for example, several black holes in the same nearly-circular orbit coalesce.[31]

Black-hole merger recoil

An unexpected result can occur with binary black holes that merge, in that the gravitational waves carry momentum and the merging black-hole pair accelerates seemingly violating Newton's third law. The center of gravity can add over 1000 km/s of kick velocity.[32] The greatest kick velocities (approaching 5000 km/s) occur for equal-mass and equal-spin-magnitude black-hole binaries, when the spins directions are optimally oriented to be counter-aligned, parallel to the orbital plane or nearly aligned with the orbital angular momentum.[33] This is enough to escape large galaxies. With more likely orientations a smaller effect takes place, perhaps only a few hundred kilometers per second. This sort of speed will eject merging binary black holes from globular clusters, thus preventing the formation of massive black holes in globular cluster cores. In turn this reduces the chances of subsequent mergers, and thus the chance of detecting gravitational waves. For non spinning black holes a maximum recoil velocity of 175 km/s occurs for masses in the ratio of five to one. When spins are aligned in the orbital

plane a recoil of 5000 km/s is possible with two identical black holes.[34] Parameters that may be of interest include the point at which the black holes merge, the mass ratio which produces maximum kick, and how much mass/energy is radiated via gravitational waves. In a head-on collision this fraction is calculated at 0.002 or 0.2%.[35] One of the best candidates of the recoiled supermassive black holes is CXO J101527.2+625911.[36]

Halo drive for space travel

It has been hypothesized that binary black holes could transfer energy and momentum to a spacecraft using a "halo drive", exploiting the holographic reflection created by a set of null geodesics looping behind and then around one of the black holes before returning to the spacecraft. The reflection passing through these null geodesics would form one end of a laser cavity, with a mirror on the spacecraft forming the other end of the laser cavity. Even a planet-sized spacecraft would thereby accelerate to speeds exceeding the approaching black hole's relative speed. If true, a network of these binary black holes might permit travel across the galaxy.[37]

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External links

- Binary Black Holes Orbit and Collide (https://www.youtube.com/watch?v=L478ZPy_2Ys)
- Merritt, David; Milosavljević, Miloš (2005). "Massive Black Hole Binary Evolution" (https://web.archive.org/web/20120330074938/http://relativity.livingreviews.org/Articles/lrr-2005-8/). *Living Reviews in Relativity*. **8**: 8. arXiv:astro-ph/0410364 (https://arxiv.org/abs/astro-ph/0410364). Bibcode:2005LRR.....8....8M (https://ui.adsabs.harvard.edu/abs/2005LRR.....8....8M). doi:10.12942/lrr-2005-8 (https://doi.org/10.12942%2Flrr-2005-8). S2CID 119367453 (https://api.semanticscholar.org/CorpusID:119367453). Archived from the original (http://relativity.livingreviews.org/Articles/lrr-2005-8/) on 2012-03-30.