Reasons to be cheerful, part III
–
some scenarios for LIGO detection

Steinn Sigurdsson & Michael Sipior

Department of Astronomy & Astrophysics
Penn State

Compact binary mergers

We know observationally that there are NS–NS binaries which will merge in less than a Hubble time.

Expect gravitational radiation emission from sources with total mass $M = (M_1 + M_2)\,\mathrm{M}_\odot$, reduced mass $\mu = M_1 M_2 / M\,\mathrm{M}_\odot$

$M_{chirp} = (M_1 M_2)^{3/5}/(M_1 + M_2)^{1/5}$, $h_c \propto M_{chirp}^{5/6}$ (eg. Thorne 1994).

NS-NS mergers detectable to 10R+ Mpc.

Rate of mergers usually estimated from rate estimated for Milky Way. Rate is R_6 per million years per Milky Way.

Number density of "Milky Way like" galaxies $\sim 10^{-2}\,h^3\mathrm{Mpc}^{-3}$. $R_6 \sim 1 \Rightarrow 1$ merger per year to $r \sim 200/h$ Mpc (Phinney 1991, Narayan et al 1991).

Current estimate $h \sim 0.6 - 0.7$

Theoretical estimates for R_6 systematically higher than from observations. See eg Kalogera et al (2000, 2001), Grishuk et al (2001).

Theoretical Estimates

About 1% of stars formed evolve to neutron stars Probably over 50% of stars are in binaries

The secondary mass function of high mass binaries is thought to be flat. Consistent with $q = M_2/M_1$ uniform on $[0, 1]$.

Expect birth rate of binaries which lead to two neutron stars forming to be few$\times 10^{-3}$ y^{-1}.

So, $R_6 \sim 1$ implies one system in few thousand becomes a tightly bound NS–NS binary that merges in a Hubble time.

This is the essence of the problem we face, the branching ratio for the merger channels is small, and the input physics is uncertain, so the fractional uncertainty for any given channel can be large, and hence the cumulative rate summed over all channels is very uncertain.

We can check this theoretically:

mass function

inital mass of star which becomes neutron star/black hole

binary fraction,

distribution of orbital parameters

mass transfer during stellar evolution

kick distribution

Binaries break up due to mass loss during supernova (primarily during second supernova).

Can remain bound if mass loss from secondary is significant ($M_2(t_{SN}) < 5.5$M$_\odot$ - true for small fraction of systems.

Or: there is asymmetric transfer of momentum during supernova, net "kick" on proto-neutron star, gives impulse which adds vectorially to Δv due to mass loss (in binary rest mass frame).

$$v_{kick} \sim 10^{2.3\pm0.5}\ \mathrm{km\,s^{-1}}$$

If well matched to v_{orb} some small fraction finish in short period orbits with $v_{orb}(final) \sim v_{kick}$.

Consistent with observations. Several estimates of kick amplitude; eg Hansen & Phinney - gaussian at 190 kms^{-1}, others comparable, some invoke bi–modal kicks.

Kicks are most likely due to asymmetries in neutrino emission during core collapse - modulated by hydrodynamics? (see Lai et al 2000)

Poorly understood. Microphysics not well determined. Mostly constrained by energetics ($\frac{1}{2}M_{NS}v_{kick}^2 \sim 6 \times 10^{47}$ erg). But - $p \sim 6 \times 10^{40} \Rightarrow pc \sim 2 \times 10^{51}$ so require significant neutrino asymmetry for $E_{tot} \sim 10^{53}$ ergs.

Theory has $R_6 = 3 - 100$

Indirect observational constraints $R_6 \lesssim 10$, conservative theory estimates get R_6 "right" (Zwart et al, Bulik et al, Bloom et al 1999).

May be "non–luminous" channels for NS–NS formation, or we may be underestimating rapidly merging NS-NS systems (Kalogera et al 2001, Grishuk et al 2001). Progenitor problem constraints somewhat flexible - see instantaneous massive star population, R_6 draws from mean distribution.

- ## NS–BH binaries

No observed examples. One of the "Holy Grails" of pulsar observations.

Indirect constraints suggest $R_6 < 10$. Very poor theoretical constraints. Mass at which star becomes BH rather than NS is not well known. Secondary fate affected by mass transfer - non–trivial to map secondary mass function to secondary remnant type.

LIGO rate should be measured.

• BH–BH binaries

Gain significantly in h_c if M_{BH} can be large ($\gtrsim 10\,\mathrm{M}_\odot$). Gain in detection volume may offset scarcity.

About 10^{-4} of stars become black holes.

Exact fraction quite uncertain.

Current estimates are black holes start forming

for progenitor masses $\sim 20 - 25\,\mathrm{M}_\odot$

Estimate direct collapse to BH at $40+\,\mathrm{M}_\odot$

Implies significant "fuzzy" zone where star collapse

involves supernova. Fate depends on details of envelope loss. (Fryer 1999)

Looks good. Mass loss is modest, no Blaauw kick to breakup binary. Formation of event horizon should preclude asymmetric kick.

If 50% are in binaries and 30% have massive secondaries, then naive $R_6 \sim 15$! Dominates rate.

PROBLEM: modern stellar evolution calculation (Portegies Zwart & Yungelson 1998) suggest BH–BH that are detached (and don't merge to single star) lose so much mass through winds, that the BH–BH end up in wide circular orbits with orbital periods > 10 days and can not merge through gravitational radiation.

Conclusion effective merger rate is ZERO.

SOLUTIONS:

- change progenitor mass
- harden binaries
- reintroduce kicks

Making low mass BH

Proposal is to make making BH easier (eg Bethe & Brown 1998)

Requires soft EOS. Low critical mass for NS to collapse to BH.

Two channels: make BH out of lower mass stars, avoid strong wind loss phase. End up in tighter BH–BH binaries.

or, make BH during inspiral in envelope of secondary (make NS-BH binaries preferentially). Require super–Eddington accretion with mass reaching NS surface to increase gravitational mass.

Attractive. Can be disproven if massive NS is ever found.

RXTE data + theory of QPOs suggest EOS is hard. Implies NS don't collapse to BH easily through accretion from stellar envelope and critical mass for BH formation in core collapse is high.

Does significant fraction of matter reach NS surface. Energy release should unbind envelope. Neutrino emission? NS magnetic field important.

Open question still, but looking weak.

Hardening of binaries

Accept that all BH–BH binaries are long period.

In dense stellar environment stars encounter binaries and exchange E, J. On average if $\frac{1}{2}M_* v_\infty^2 < E_{bin}$ then binary loses energy to star (Heggie 1975, Hut & Bahcall 1983, Sigurdsson & Phinney 1993).

So BH–BH binary axis shrinks. Mean shrinkage $\sim 40\%$ per close encounter. Rate of encounters $\sim n_* \sigma v_\infty$, where $\sigma \sim \pi a^1 (1 + (v_{orb}/v_\infty)^2$ is the cross–section of the binary allowing for gravitational focusing.

This works best in high density low dispersion systems. ie in globular clusters. With $\sim 10^6$ stars each, 100+ clusters per galaxy, have few BH–BH binaries in each cluster at formation. Segregate through dynamical friction and interact.

If BH–(BH–BH) interact, then recoil in c–o–m during encounters will eject BH–BH to outskirts of cluster, or completely from cluster.

*–(BH–BH) encounters only harden don't eject.

Two questions:

do BH–BH binaries get tight enough for grav rad before being ejected?

do BH-BH binaries all merge in early life of cluster?

Sigurdsson & Hernquist 1993, Portegies Zwart & McMillan 2000.

Sigurdsson & Hernquist 1993 considered this. Concluded most of BH–BH mergers early, now ~ 1 per cluster per t_H^{-1}. Also only work for clusters with $n \gtrsim 10^6$ pc^{-3}.

Allows BH–BH binaries formed with $a > 10^3 AU$ to merge in finite time.

Mergers that take place are biased towards most massive BH formed as they are preferentially retained in binaries and cluster.

So $R_6 \sim 10^{-3}$. Competitive with NS–NS merger if detectable to distances > 10 times larger; or if global rate is considerably higher than Milky Way rate

Best bet is if M_{BH} extends to many 10s of $M_\odot$.

Rate is enhanced by young clusters forming in local universe - BH–BH merger rate there $10\times$ larger per dense cluster.

Some galaxies have higher specific frequency of dense clusters. Also, may have had many dense clusters now destroyed by tidal disruption or evaporation.

NS $\rightarrow$ BH through accretion channel also works in clusters. May enhance rate if AIC of NS to BH is effective.

NS–NS and BH–BH binaries in clusters have different J vs S correlations than do primordial binaries. In principle could test if sample is measured!

Giving BH a kick

Lipunov, Postnov & Prokhorov (1996, 1998 etc) note that if BH gets kick on formation then merger rate is enhanced.

Get $R_6 > 10^3$ for "tuned" kicks. BH–BH dominate merger rate for any $R_6 \gtrsim 0.1$. (cf Grishuk et al 2001, Belczynski & Bulik 1999).

PROBLEM: assuming BH receive kick on formation is completely ad hoc. In particular, if ν emission is what causes momentum flux asymmetry, then event horizon formation will terminate any asymmetry and there is no kick.

Observe ~ 10 BH binaries in galaxy. Have low mass companions (selection effect). Suggest little or no kick. Also can observe BH binary speed relative to local standard of rest.

One exception. Nova Sco (aka GRO J1655-40). Orosz et al 1995 find it has significant $v_{lsr} \sim 155\ \mathrm{km\,s^{-1}}$. Israelian et al 1999 find system consistent with having been in a supernova. Brandt, Podsiadlowski & Sigurdsson (1995) conjecture this is because the BH formation was delayed.

Two scenarios:

formed as NS. AIC to BH after accreting from companion. This now can't work. Companion never had enough mass.

or, formed with mass too high for NS, but J too high for BH. Delayed collapse while grav rad sheds J and even horizon forms.

Meanwhile neutrinos escape and there is kick.

Conjecture: a small fraction of BH form with similar momentum change at birth as NS do, but with Δv smaller by M_{NS}/M_{BH}. So expect typical velocities of 50–100 km/sec,

Well matched for longer period binaries to become tight eccentric binaries. Using Postnov & Prokhorov's numbers, expect $R_6 \sim 30 f_{delay}$ where f_{delay} is the fraction of BH that form with delayed horizon formation.

Observationally $f_{delay} \sim 0.1$ - with large uncertainty.

Consistent with scenario where high mass primary form BH with $M_1 \gtrsim 7\mathrm{M}_\odot$. Lower mass secondary in detached orbit form BH with delayed horizon formation - $M_2 \sim 3 - 7\mathrm{M}_\odot$.

Progenitor cut for delayed formation somewhere in $25 - 40\mathrm{M}_\odot$ range. May depend on details of mass loss, rotation, B–fields, mass transfer.

We ran a set of population synthesis models, based on Pols & Marinus (1994), exploring specifically the rate of BH–BH mergers through the Nova Sco like channel only.

We varied the kick, the IMF and the mass transfer rate as a function of initial mass to explore the sensitivity of the simulation results to the parameters known to be most important.

We find $R_6 = 0.05 - 10 f_{delay}$, depending on our choice of input parameters, with the canonical Salpeter IMF and Hansen & Phinney kick distribution giving $R_6 = 2 f_{delay}$. Note that we assume kicks only apply to BHs whose progenitor stars were between 25 and 40 solar masses, so f_{delay} can in principle be larger than 1.

The same choice of input parametes gives the NS–NS merger rate as $R_6(NS - NS) = 3$, and therefore predicts that BH–BH mergers dominate the signal rate if $f_{delay} \gtrsim 0.1$. The NS–NS and BH–BH merger rates scale roughly equally as the input parameters are varied.

The Nova Sco like BH–BH systems have primaries typically of $8-12M_\odot$ and secondaries of $4-6M_\odot$.

Prediction: secondary has maximal spin.

This is a consequence of the heuristic physical picture in which event horizon formation is delayed, allowing the asymmetric flux of whatever it is that causes kicks to escape to infinity. The simplest and most general scenario is for the angular momentum of the nascent black hole to exceed the critical value, delaying event horizon formation until the angular momentum is shed.

Formation rate in this scenario is comparable with NS–NS merger rate (optimistically) but detection rate is stronger because of volume gain.

Gives cleaner signal for LIGO, better relativity, less nuclear physics.

Conclusions

- simple BH–BH formation + merger through gravitational radiation seems unlikely to happen at a significant rate
- there are other channels for BH–BH to form and merge
- low mass BH–BH or BH–NS would provide strong constraints on EOS at high ρ
- dynamical hardening of binaries provides "guaranteed" channel for BH–BH merger. May not be efficient enough for interesting rates. May be relevant if black hole mass function extends to high masses.
- partial kick for even a few % of BH formed could dominate merger rate and give binaries that dominate LIGO rate with several per year.