At the end of January 1996, the day before I was to return to Stony Brook, Kip Thorne came to the office Hans and I shared at Caltech. He said the production of gravitational waves that LIGO (the Laser Interferometer Gravitational-Wave Observatory) should measure from coalescing neutron stars had been estimated by several research workers theoretically, but mergers of neutron stars and black holes had not received as much attention. Hans and I, he continued, were good at calculating things that had not been seen. Could we calculate the contribution of those less-studied mergers?

The previous year I had found that the accepted scenario for evolving a neutron-star binary resulted in a binary comprising a neutron star and a low-mass black hole.[3] So I knew that binaries with a neutron star and a black hole would give at least an order of magnitude more mergers than neutron-star binaries. I said to Hans, "You've now calculated Roman numeral VI of your theory of supernovae. It's time to change." After all, he was only 90. I went on to say that we now had a topic to work on next year at Caltech. He replied, "Oh, no! I want to begin now." So after I got back to Stony Brook, I sent him a 20-page paper by Evert Meurs and Edward van den Heuvel.[4] A few days later, I received from him a page-and-a-half fax, in which he'd derived their main conclusions. "I don't seem to have done it as accurately as they did, but I got the same results," he noted.

We wrote a paper, "Evolution of Binary Compact Objects that Merge," that I think is the best thing Hans and I did.[5] The paper appears in about the middle of the collected works[6] that I edited along with Hans and Chang-Hwan Lee. It and the papers that followed are mostly "about the future," like Ejlert Lövborg's manuscript in Henrik Ibsen's great play *Hedda Gabler*. But since Lee coauthored several of those papers, they cannot be thrown into the fire and burned; in any case, he has computer backups of them.

Hans and I made lots of predictions that only the future will test. The chief among those will not be checked for at least a decade, when LIGO II is completed: We predict that LIGO II will find 20 times more mergers of low-mass black-hole, neutron-star binaries than of neutron-star binaries.

LIGO-G060002-00-R

Population Statistics give a quantitative prediction for the # of gravitational mergers.

Lifetime of massive stars

$$\propto \frac{1}{M^{2.5}}$$

Relative # $\propto \frac{1}{M^{2.5}}$

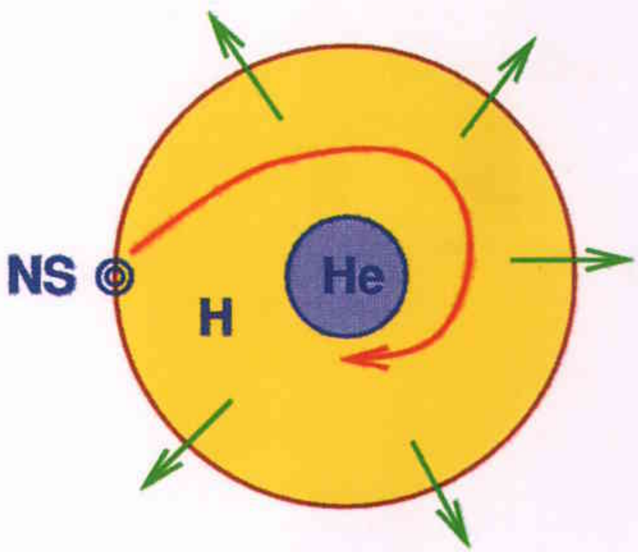
Binarity ~ 0.5

From 2 SN events per century in the Galaxy can give an absolute normalization to # of mergings.

50% survive 1st explosion
50% survive 2nd explosion
forming the ~~two~~ binary neutron stars.

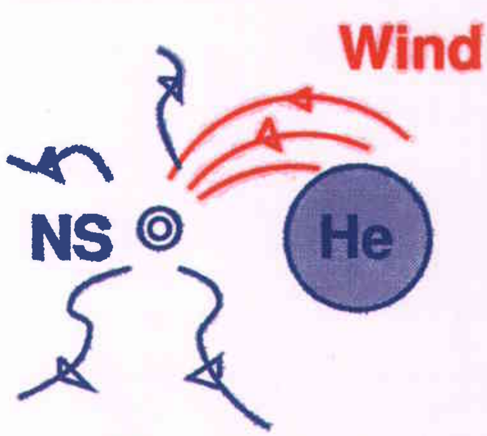
For the double He star scenario need 4%. Factor of 100 decrease for binary neutron stars, but only 1/4 for neutron-star, black-hole binaries

What is Supposed to Happen



Neutron star spirals in. Orbital energy loss is coupled, through dynamical friction, to the envelope, which is expelled.

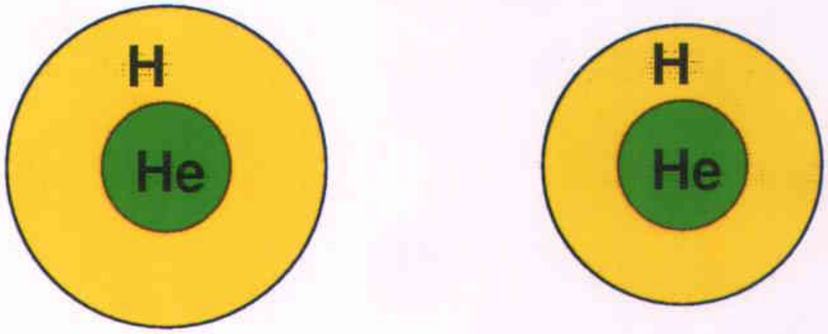
Left with



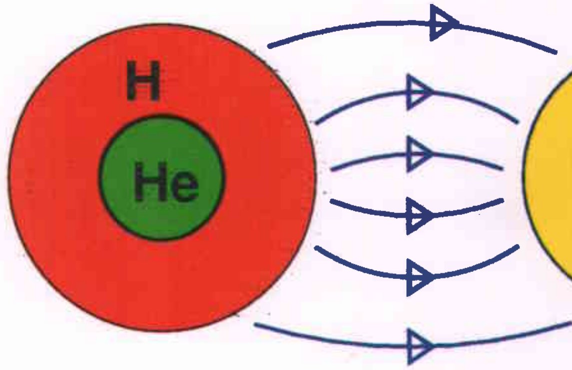
We do see one such object Cyg X-3. But there should be $\geq$ 100 if this is the usual outcome.

Evolution of Binaries : Pictorially

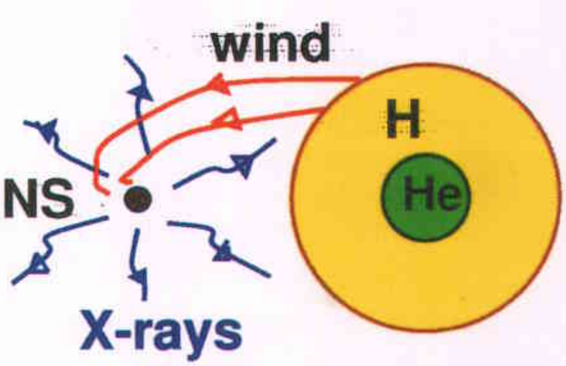
Start with two large O-star ($\sim 20\ M_\odot$) in Binary

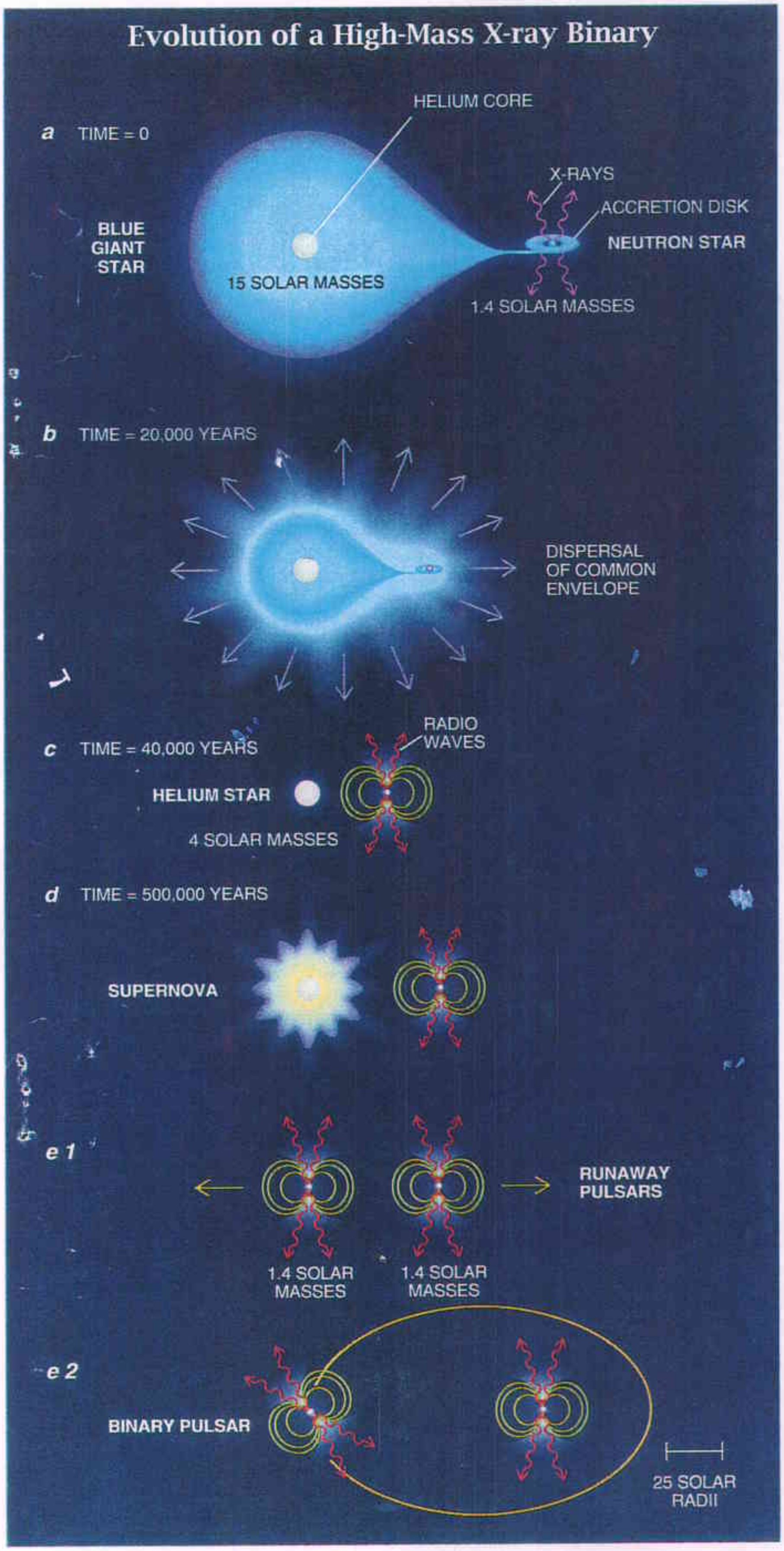


More massive one evolves (goes into red giant), pours mass on less massive one



He-core then explodes $\Rightarrow$ neutron star





van den Heuvel & van Paradijs 1993
(Nov.) Sci. Am. p. 38.

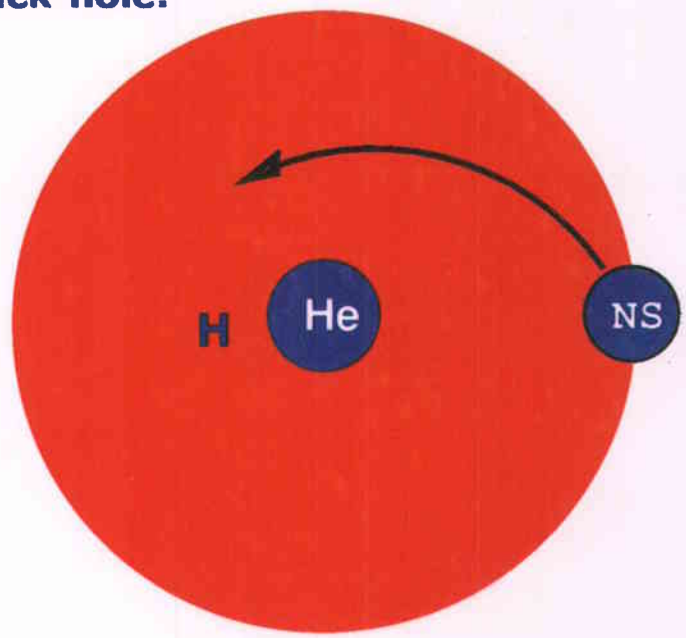
Chevalier 1989, ApJ 346, 847
1993, ApJL 411, 33.

G. E. B. ApJ 440, 270
1955

What we believe does happen

H.A. Bethe & G.E.Brown
ApJ 506, 780 (1998)

In the dispersal of the envelope, the neutron star accretes mass ⟶ black hole.

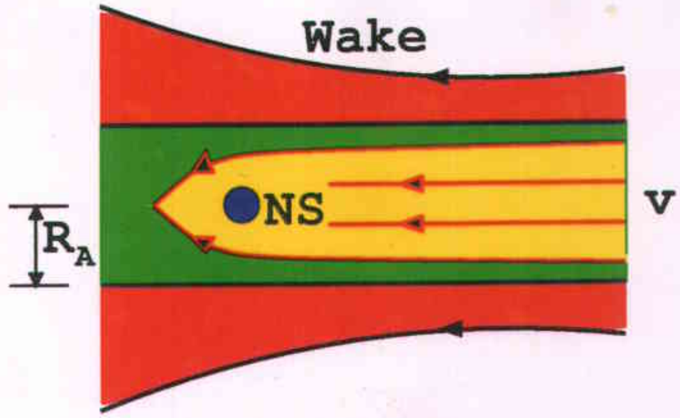


When the neutron star is in the common envelope

$$\dot{M} = \pi R_A^2 \rho_\infty v \qquad (v = vel.)$$

with R_A defined by

$$\frac{1}{2} v^2(R_A) - \frac{GM}{R_A} = 0$$



First sit on the NS & consider work it does in bringing matter in the accretion cylinder to rest.

$$F = \frac{dP}{dt} = v\frac{dM_A}{dt}$$

$$\dot{E} = Fv = v^2\frac{dM_A}{dt} = \underbrace{\frac{c_d}{2}v^2\frac{dM_A}{dt}}$$

Now include the wake

$c_d/2 > 1$ (~ 3)

$v^2 = G(M_A + M_B)a^{-1}$ **(Kepler), so**

$$\dot{E} = c_d\frac{G}{2a}(\cancel{M_A} + M_B)\dot{M}_A \qquad \text{(I)}$$

but, $E = \frac{1}{2}GM_AM_Ba^{-1}$ **also, so**

$$\dot{E} = \frac{G}{2}(\dot{M}_AY + M_A\dot{Y}) \qquad \text{(II)}$$

Two variables : $\dot{M}_A$ **&** $Y \equiv M_B/a$ **& two eqns.**

Know $M_{B,i} \simeq 10\ M_\odot$

$M_{B,f} = M_{He} \simeq 3\ M_\odot$

(Only the ratio $M_{B,f}/M_{B,i} = 0.3$ is used.)

In-Spiral fast, ∼ 1 year Relation

$$-\frac{dE}{dt} = \frac{dM_A}{dt}\frac{1}{2}V^2 c_d \qquad \textbf{Drag}$$

$$-E = \frac{1}{2}GM_AM_Ba^{-1}$$

Set $M_B/a = Y$

$$\frac{-E}{\frac{1}{2}G} = M_AY$$

$$V^2 \approx GM_Ba^{-1} = GY$$

$$-\frac{\dot{E}}{\frac{1}{2}G} = Y\dot{M}_Ac_d$$

$$\frac{d}{dt}(M_AY) = \dot{M}_AY + M_A\dot{Y}$$

$$\frac{\dot{Y}}{Y} = \frac{\dot{M}_A}{M_A}(c_d - 1)$$

$$c_d = 2\ln(b_{max}/b_{min}) \approx 6$$

$$M_A \sim Y^{1/(c_d-1)} = Y^{1/5}$$

$$E_f = \frac{1}{2}GM_{Ai}Y_i\left(\frac{Y_f}{Y_i}\right)^{6/5}$$

$$\frac{\dot{M}_{\rm A}}{M_{\rm A}} = \frac{1}{(c_d - 1)}\frac{\dot{Y}}{Y} \quad \Rightarrow \quad M_{\rm A} \propto Y^{1/(c_d-1)} = Y^{1/5}$$

$$\boxed{\frac{M_{{\rm A},f}}{M_{{\rm A},i}} = \left(\frac{Y_f}{Y_i}\right)^{1/5}}$$

$$\begin{aligned} E_f &= \frac{1}{2} G M_{{\rm A},f} \frac{M_{{\rm B},f}}{a_f} = \frac{1}{2} G M_{{\rm A},i} Y_i \left(\frac{Y_f}{Y_i}\right)^{6/5} \\ &= \frac{0.6}{\alpha_{ce}} G \, \frac{M_{{\rm B},i}^2}{a_i} \simeq 1.2 \, G \, \frac{M_{{\rm B},i}^2}{a_i} \end{aligned}$$

$$\boxed{\text{so} \quad \left(\frac{Y_f}{Y_i}\right)^{1.2} = 2.4 \, \frac{M_{{\rm B},i}}{M_{{\rm A},i}} \simeq 2.4 \left(\frac{15 M_\odot}{1.4 M_\odot}\right)}$$

$$\frac{Y_f}{Y_i} = 15 \qquad \& \qquad \frac{M_{{\rm A},f}}{M_{{\rm A},i}} = 1.7$$

$$\boxed{M_{{\rm A},f} = 2.4 M_\odot}$$

$$\frac{a_i}{a_f} = \frac{M_{{\rm B},i}}{M_{{\rm B},f}} \frac{Y_f}{Y_i} = 50$$

$$\boxed{0.5 \times 10^{13}\ {\rm cm} < a_i < 1.9 \times 10^{13}\ {\rm cm}}$$

Binary separations distributed logarithmically with $\log a$.
$\sim$ 20% of binaries lie in this interval.

Accretion

$$\dot{E} = \frac{1}{2} C_d G (M_A + M_B) a^{-1} \dot{M}_A \qquad (350)$$

$$E = \frac{1}{2} G M_A M_B a^{-1} \qquad (351)$$

E here is the gravit. energy between A & B. Initially,

$$E_i = \frac{3}{5} G M_{Bi}^2 / a_i \qquad (526)$$

(350) can be integrated, using $M_B a^{-1}$ and M_A as variables. From (351)

$$\dot{E} \sim \frac{M_B}{a} \dot{M}_A + \frac{d}{dt}\left(\frac{M_B}{a}\right) M_A \qquad (527)$$

Neglect $M_A \ll M_B$ in (350), then

$$\dot{M}_A \frac{M_B}{a} (c_d - 1) = M_A \frac{d}{dt}\left(\frac{M_B}{a}\right) \qquad (528)$$

$$M_A \sim \left(\frac{M_B}{a}\right)^{\frac{1}{c_d - 1}} \sim \left(\frac{M_B}{a}\right)^{0.2} \qquad (529)$$

$$E_f = 2 E_i$$

$$M_{Af} \frac{M_{Bf}}{a_f} = 2.4 \frac{M_{Bi}^2}{a_i} \qquad (530)$$

$$M_{Ai} \left\{\frac{(M_B/a)_f}{(M_B/a)_i}\right)^{1.2} = 2.4 M_{Bi} \qquad (531)$$

$$\frac{(M_B/a)_f}{(M_B/a)_i} = \left(2.4 \frac{M_{Bi}}{M_{Ai}}\right)^{5/6} = \left(2.4 \frac{16}{1.4}\right)^{5/6} = 27^{5/6} = 15.6 \qquad (5\ldots)$$

$$\frac{M_{Af}}{M_{Ai}} = 15.6^{1/5} = 27^{1/6} = 1.73 \qquad (533)$$

Conclusion

Conventional theory for evolving binary neutron star doesn't work because, in the common envelope stage, the neutron star will generally accrete [G.E.B. ApJ, 440, 270, 1995]

$$\Delta M V_{N.S.}^2 \sim E_{binding}(H - envelope)$$

or $\Delta M \gtrsim 1 M_\odot$. NS $\longrightarrow$ black hole !

There is a way to avoid this.

One way to avoid the neutron star in common envelope is to begin with such nearly equal mass O- or B- stars that they will burn He at the same time. These two He stars will be in common envelope

and expel it by dynamical friction.

The later explosion of the two He stars will give a NS binary in which the two neutron stars have nearly equal masses (& other desirable characteristics)

[Tilo Wettig & G.E. Brown, NEW ASTRONOMY 1 (1996) 17.]

In the double He star scenario, a lower mass companion progenitor would be favored for 1913+16 by factor 2^5.

Neutron Star - Neutron Star Binaries

1518+49	$1.56^{+0.13}_{-0.44}$	1518+49 companion	$1.05^{+0.45}_{-0.11}$
1534+12	$1.3332^{+0.0010}_{-0.0010}$	1534+12 companion	$1.3452^{+0.0010}_{-0.0010}$
1913+16	$1.4408^{+0.0003}_{-0.0003}$	1913+16 companion	$1.3873^{+0.0003}_{-0.0003}$
2127+11C	$1.349^{+0.040}_{-0.040}$	2127+11C companion	$1.363^{+0.040}_{-0.040}$
J0737−3039A	$1.337^{+0.005}_{-0.005}$	J0737−3039B	$1.250^{+0.005}_{-0.005}$
J1756−2251	$1.40^{+0.02}_{-0.03}$	J1756−2251 companion	$1.18^{+0.03}_{-0.02}$

- All masses are < 1.5 $M_\odot$
- 1534, 2127: masses are within 1%
- J0737, J1756: ΔM = 0.1 - 0.2 $M_\odot$

Message-Id: <9407062120.AA02367@rri.ernet.in>
To: vtrimble@astro.umd.edu, vtrimble@uci.edu
Subject: Referee's report
Cc: dipankar

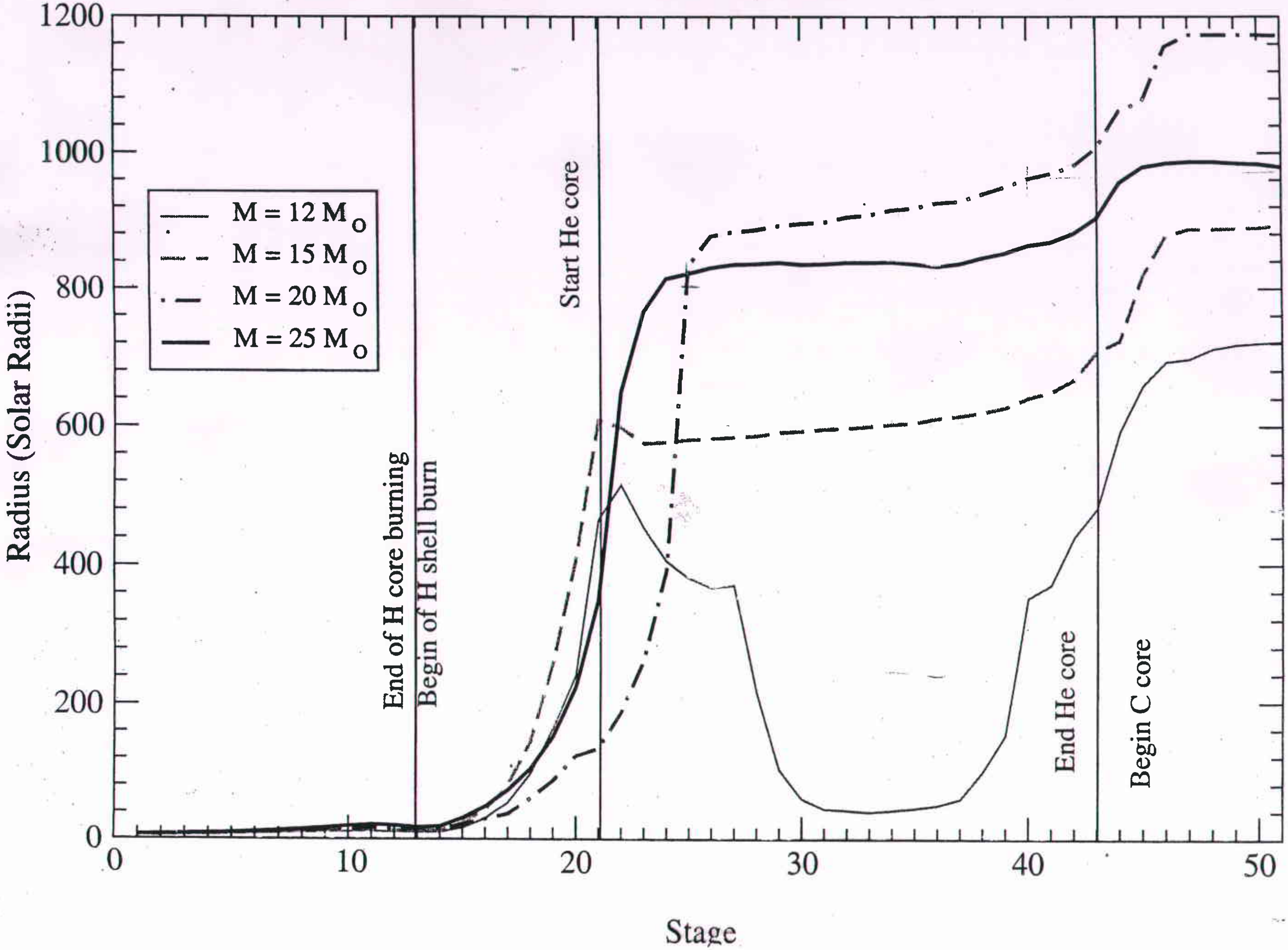
Dear Virginia,
Here is a report on the article by G. E. Brown that you sent me for refereeing. The paper seems very good, and should surely be published. I am putting a copy of the report in the mail, but am retaining the manuscript.
Best regards,
Dipankar.

Referee's report on the article "Neutron Star Accretion and Binary Pulsar Formation" by G. E. Brown. Paper number 30817. Sent on 9/6/94

This paper explores the outcome of the Common-Envelope (CE) phase of the evolution of a binary system containing a neutron star and a massive star. CE evolution, although commonly invoked as an explanation of the tight orbit of double neutron star binaries, remains one of the most poorly understood phases of the evolution of binary systems. The author attempts to understand the consequences of heavy accretion inside a common envelope, and confirms the startling conclusion of Chevalier (1993) that a neutron star is unlikely to survive the accretion process. If this is true, then contrary to the widely held view, double neutron star binaries cannot be the products CE evolution. The author provides an interesting argument connecting the dynamical friction in the common envelope and the total amount of matter accreted in support of this result. He also speculates on a possible alternative route for the formation of compact binaries containing two neutron stars.

Stellar evolutionary models (Z = 0.020)

Schaller et al. 1992 A&AS, 96, 269

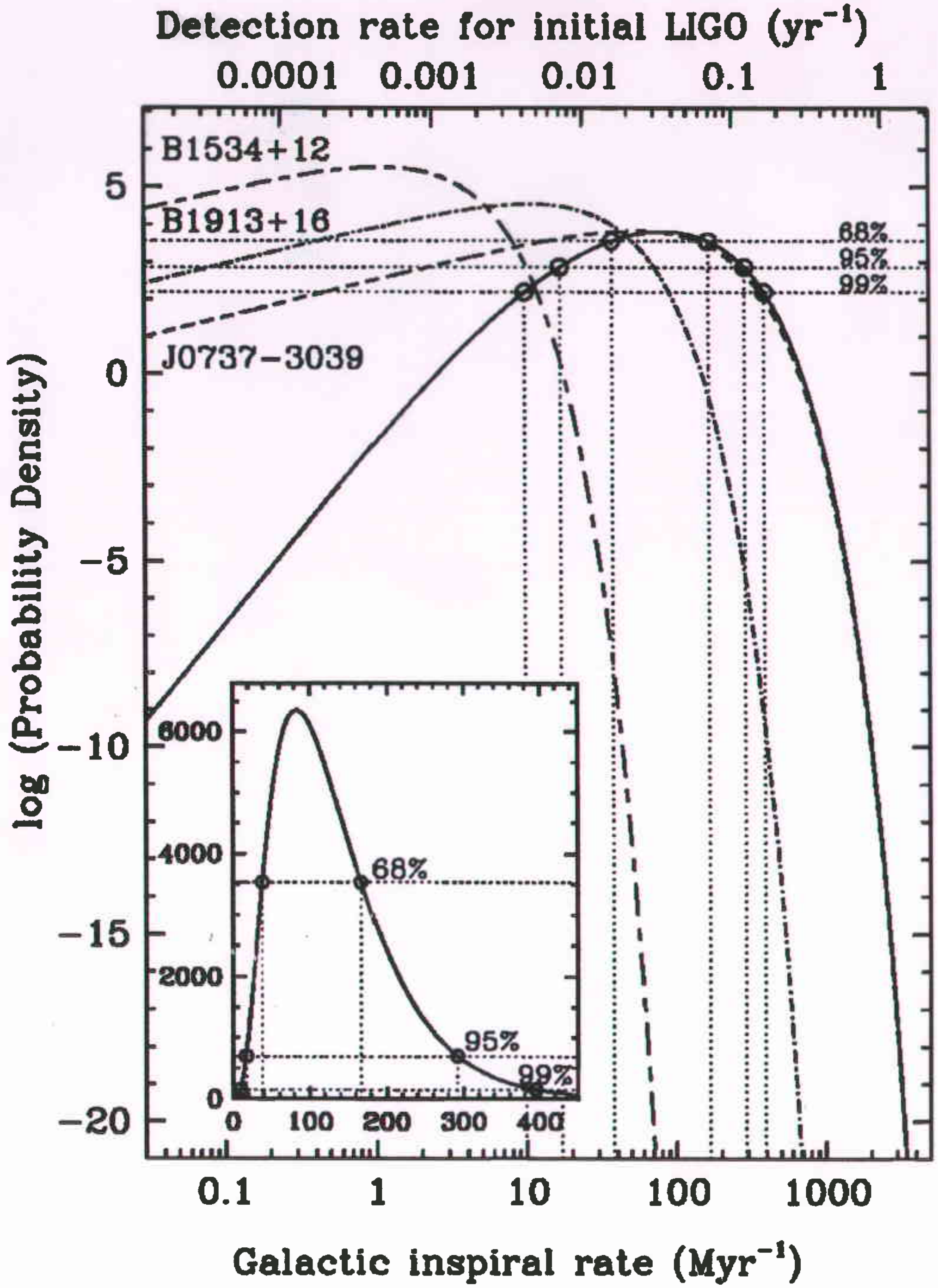


Predicted LIGO Detection Rates (yr^{-1}).

Binary Type	Initial LIGO	Advanced LIGO	Chirp Masses ($M_\odot$)
NS-NS†	0.0348	187	1.0 - 1.3
BH-NS††	0.696	3740	1.3 - 2.7
BH-BH**	0.58	2450	~ 6
Total	1.31	6377	

$$R_{\mathrm{eff}} = R_0 \left(\frac{M_{\mathrm{chirp}}}{M_\odot}\right)^{5/6}, \qquad M_{\mathrm{chirp}} = \mu^{3/5} M_{\mathrm{tot}}^{2/5}$$

R_0=17 Mpc (initial LIGO), 280 Mpc (advanced LIGO)



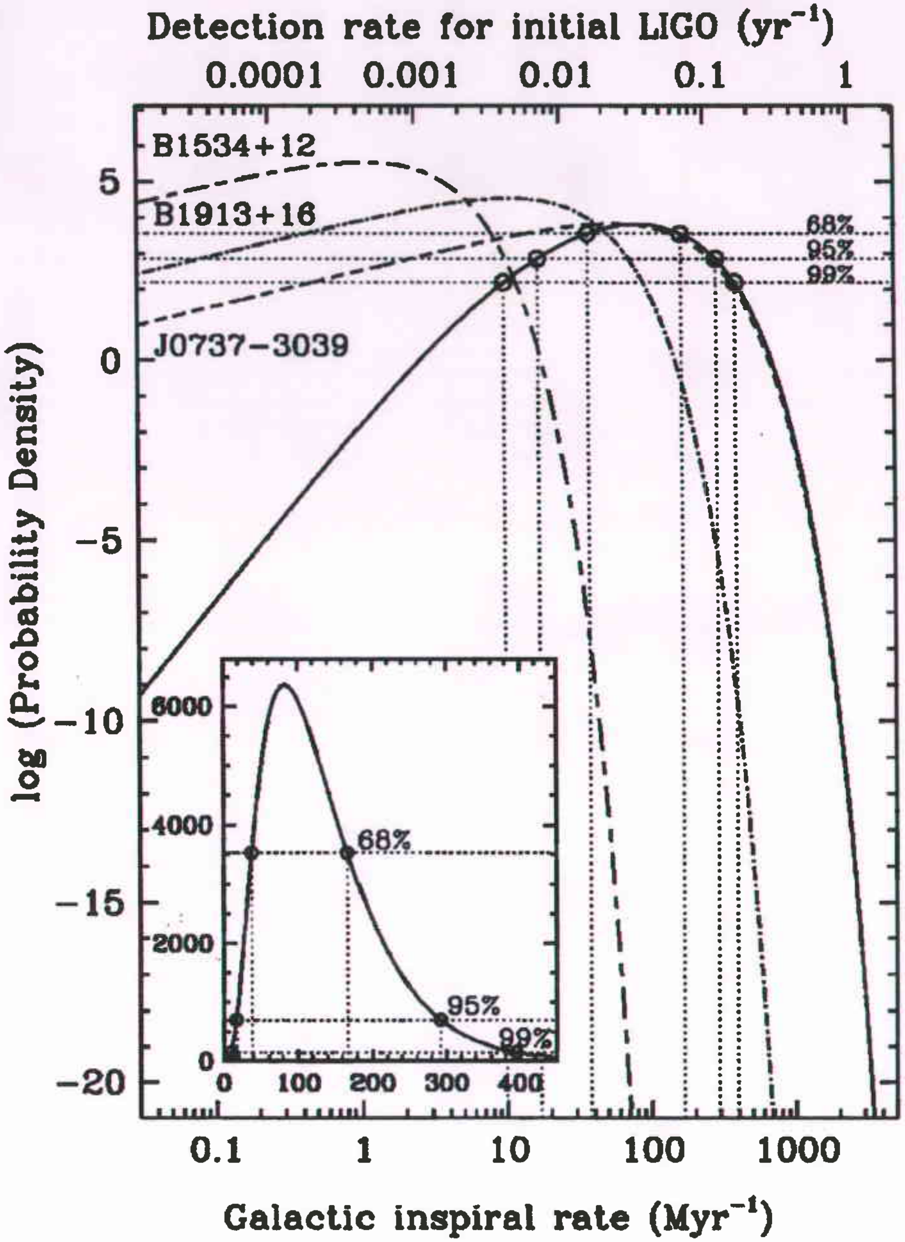
Due to J0737-3039 LIGO detection rate was increased by 8 !

weak radio signal:
1/6 of B1913+16

short coalesce time:
1/2 of B1913+16

Initial LIGO
0.035 event/year

Advanced LIGO
187 event/year



Q) Why is it so important to Bethe/Brown/Lee scenario ?

- Consistent with $M_{NS}^{max} = 1.5 M_\odot$
- 20 more LMBH/NS mergers for LIGO than NS/NS mergers

Why haven't we observed any LMBH–NS binaries?

Neutron stars like the Crab pulsar are formed with high magnetic fields

$$B \sim 5\times 10^{12}\,G$$

Spin down in a time $\sim 5\times 10^{6}$ yrs and then disappear into the graveyard of neutron stars

($B_{12}/P^2 \gtrsim 0.2$ to pulse)

(min voltage from polar cap)

The pulsars in relativistic binaries are recycled, fields $B \sim 10^{10}\,G$, presumably having been brought down by mass accretion.

Observability Premium $\Pi \sim \dfrac{10^{12}\,G}{B}$

relative time a pulsar is observable.

The recycled binary pulsars have pulsar magnetic fields $\sim 10^{10}\,G$. ∴ they are observable for ~ 100 times longer ~~than~~ "fresh" binaries.

In population syntheses hard to get more than $1-2\times10^{-4}$ mergers of compact objects / yr, normalizing to the SN rate. (NS → BH just rearrange.)

But earlier in the Universe the star formation rate was higher

Ehud Nakar, Avishay Gal-Yam & Derek Fox astro-ph/0511254

The merging binaries were formed long ago

$$\tau \sim 0.8\,\tau_{hubble}$$

SFR of Porciani & Madau

$$\propto \frac{e^{3.4z}}{e^{3.4z}+22}\;\frac{\left[\Omega_m(1+z)^3+\Omega_\Lambda\right]^{1/2}}{(1+z)^{3/2}}$$

Schematic: Take $z=1$, binarity with $\tau = 0.5\,\tau_{hubble} \sim 8$ Gyr

rms radius $= .8\times8 \sim 6$ Gyr

$$SFR = 0.36$$

Increase by factor $\dfrac{0.36}{1/22} = 8$

Increase in LIGO merging rate above ~ 1/yr is due to SFR.

Chirp Masses

Volume of observation $\propto M_{chirp}^{5/2}$

Take low-mass black holes to be $2 M_\odot$

N.S. mass $= 1.2\ M_\odot$

$(\text{Chirp mass})^{5/2} = 3.15$ vs 12.4 for $10 M_\odot$ black hole.

Binary N.S. $1.2 M_\odot$ each

$(\text{Chirp mass})^{5/2} = 1.11\ M_\odot$

New nucl-th/0504029 G.E.B., C-H. Lee, Mannque Rho

Calculate about the fixed point
$n_c \lesssim 4 n_0$

No Ψ^4 contribution; only the Weinberg-Tomozawa vector mean field.

Harada - Yamawaki

$$m_V^2 = a f_\pi^2 g_V^2$$

$a = 2$ (vector dominance) get KFSR.

But as go to the fixed point $a \to 1$.

$f_\pi \to 0.8 f_\pi$ pionic atoms

$$\frac{g_V^{*2}}{m_V^{*2}} = \frac{1}{a^*} \frac{1}{f_\pi^{*2}}$$

$$(g_V^{*2}/m_V^{*2})_{\text{fixed point}} \Big/ (g_V^2/m_V^2)_{u=0}$$

$= 3.13$; $n_c = 3.1\, n_0$

So <u>quadratic</u> dependence on density