HIGH MASS BLACK HOLES IN SOFT X-RAY TRANSIENTS

Gap in Black Hole Masses ?

G.E. BROWN, C.-H. LEE
Department of Physics and Astronomy,
SUNY at Stony Brook, NY 11794, USA

AND

H.A. BETHE
Floyd R. Newman Laboratory of Nuclear Studies,
Cornell University, Ithaca, New York 14853, USA

Abstract. 1 We suggest that high-mass black holes; i.e., black holes of several solar masses, can be formed in binaries with low-mass main-sequence companions, provided that the hydrogen envelope of the massive star is removed in common envelope evolution which begins only after the massive star has finished He core burning. Our evolution scenario naturally explains the gap (low probability region) in the observed black hole masses.

1. Introduction

In this talk we suggest that high-mass black holes; i.e., black holes of several solar masses, can be formed in binaries with low-mass main-sequence companions, provided that the hydrogen envelope of the massive star is removed in common envelope evolution which begins only after the massive star has finished He core burning (Brown, Lee, & Bethe 1999). That is, the massive star is in the supergiant stage, which lasts only $\sim 10^4$ years, so effects of mass loss by He winds are small. Since the removal of the hydrogen envelope of the massive star occurs so late, it evolves essentially as a single star, rather than one in a binary. Thus, we can use evolutionary calculations of Woosley & Weaver (1995) of single stars.

We find that high-mass black holes can be formed in the collapse of stars with ZAMS mass $\gtrsim 20 \, M_\odot$. Mass loss by winds in stars sufficiently

1 Talk given by C.-H. Lee at the NATO Advanced Study Institute on “The Neutron Star - Black Hole Connection”, June 7 - 18, 1999, Elounda, Crete, Greece
TABLE 1. Parameters of suspected black hole binaries in soft X-ray transients with measured mass functions (Brown, Lee, & Bethe 1999). N means nova, XN means X-ray nova. Numbers in parenthesis indicate errors in the last digits.

| X-ray names | other name(s) | type | $P_{orb}$ (d) | $f(M_X)$ ($M_\odot$) | $M_{opt}$ ($M_\odot$) | $q$ | $R_{opt}$ (km s$^{-1}$) | $i$ (degree) | $M_X$ ($M_\odot$) |
|-------------|--------------|------|-------------|---------------------|----------------------|-----|-----------------|---------|----------------|
| XN Mon 75   | V616 Mon     | K4 V | 0.3230      | 2.83-2.99           | 0.53-1.22            |     |                 |         |                 |
| A 0620−003  | N Mon 1917   | K3 V | 0.5213      | 4.44-4.86           | 0.3-0.6              |     |                 |         |                 |
| XN Oph 77   | V2107 Oph    | K3 V | 0.3441      | 4.89-5.13           | 0.17-0.97            |     |                 |         |                 |
| H 1705−250  |              | K5 V | 0.4326      | 2.86-3.16           | 0.41-1.4             |     |                 |         |                 |
| XN Vul 88   | Q2 Vul       | K5 V | 0.3426      | 2.86-3.16           | 0.41-1.4             |     |                 |         |                 |
| GS 2000+251 | V404 Cyg     | K0 IV| 0.030-0.054 | 520(16)             | 43-74                | 0.58| 18.0           |         |                 |
| XN Cyg 89   | N Cyg 1938, 1959 | K0 IV | 6.4714 | 6.02-6.12 | 0.57-0.92 | | | | |
| GS 2033+338 | N Cyg 1938, 1959 | K0 IV | 0.030-0.054 | 520(16) | 43-74 | 0.58 | 18.0 | | |
| XN Mus 91   |              | K5 V | 0.4326      | 2.86-3.16           | 0.41-1.4             |     |                 |         |                 |
| GS 1124−683 |              | M0 V | 0.2127(7)   | 1.15-1.27           | 0.10-0.97            |     |                 |         |                 |
| XN Per 92   |              |      |             |                     |                     |     |                 |         |                 |
| GRO J0422+32|              |      |             |                     |                     |     |                 |         |                 |
| XN Sco 94   |              |      |             |                     |                     |     |                 |         |                 |
| GRO J1655−40|              |      |             |                     |                     |     |                 |         |                 |
| XN MX 1543−475 | A2 V | 1.123(8) | 0.20-0.24 | 1.3-2.6 | | | | | |
| 4U 1543−47  |              |      |             |                     |                     |     |                 |         |                 |
| XN Vel 93   |              |      |             |                     |                     |     |                 |         |                 |

massive to undergo the LBV (luminous blue variable) stage may seriously affect the evolution of stars of ZAMS $> 35 - 40 M_\odot$, we take the upper limit for the evolution of the so-called transient sources to be $\sim 35 M_\odot$ ZAMS mass. Both Portegies Zwart, Verbunt & Ergma (1997) and Ergma & Van den Heuvel (1998) have suggested that roughly our chosen range of ZAMS masses must be responsible for the transient sources. We believe that the high-mass black hole limit of ZAMS mass $\sim 40 M_\odot$ suggested by Van den Heuvel & Habets (1984) and later revised to $\geq 50 M_\odot$ (Kaper et al. 1995) applies to massive stars in binaries, which undergo RLOF (Roche Lobe Overflow) early in their evolution.

The most copious high-mass black holes of masses $\sim 6 - 7 M_\odot$ have been found in the transient sources such as A0620. These have low-mass companions, predominantly of $\leq 1 M_\odot$, such as K- or M-stars. In the
progenitor binaries the mass ratios must have been tiny, say $q \sim 1/25$. Following the evolutionary scenario for the black hole binary of De Kool et al. (1987), we show that the reason for this small $q$-value lies in the common envelope evolution of the binary. The smaller the companion mass, the greater the radius $R_g$ the giant must reach before its envelope meets the companion. This results because the orbit of a low-mass companion must shrink by a large factor in order to expel the envelope of the giant, hence the orbit must initially have a large radius. (Its final radius must be just inside its Roche Lobe, which sets a limit to the gravitational energy it can furnish.) A large radius $R_g$ in turn means that the primary star must be in the supergiant stage. Thus it will have completed its He core burning while it is still “clothed” with hydrogen. This prevents excessive mass loss so that the primary retains essentially the full mass of its He core when it goes supernova. We believe this is why K– and M–star companions of high-mass black holes are favored.

2. Formation of High-Mass Black Holes

We find that the black holes in transient sources can be formed from stars with ZAMS masses in the interval $20 - 35 \ M_\odot$ (Brown, Lee, & Bethe 1999). The black hole mass is only slightly smaller than the He core mass, typically $\sim 7 \ M_\odot$ (Bethe, Brown, & Lee 1999).

Crucial to our discussion here is the fact that single stars evolve very differently from stars in binaries that lose their H-envelope either on the
main sequence (Case A) or in the giant phase (Case B). However, stars that transfer mass or lose mass after core He burning (Case C) evolve, for our purposes, as single stars, because the He core is then exposed too close to its death for wind mass loss to significantly alter its fate. The core masses of single stars and binary stars are summarized in Fig. 1. Single stars above a ZAMS mass of about 20 M_⊙ skip convective carbon burning following core He burning, with the result, as we shall explain, that their Fe cores are substantially more massive than stars in binaries, in which H-envelope has been transferred or lifted off before He core burning. These latter “naked” He stars burn ^{12}C convectively, and end up with relatively small Fe cores. The reason that they do this has to do chiefly with the large mass loss rates of the “naked” He cores, which behave like W.-R.’s. In the ZAMS mass range ~ 20 – 35 M_⊙, it is clear that many, if not most, of the single stars go into high-mass black holes, whereas stars in binaries which burn “naked” He cores go into low-mass compact objects. In this region of ZAMS masses the use of high He-star mass loss rates does not cause large effects (Wellstein & Langer 1999).

The convective carbon burning phase (when it occurs) is extremely important in pre-supernova evolution, because this is the first phase in which a large amount of entropy can be carried off in ν ¯ν-pair emission, especially if this phase is of long duration. The reaction in which carbon burns is ^{12}C(α, γ)^{16}O (other reactions like ^{12}C + ^{12}C would require excessive temperatures). The cross section of ^{12}C(α, γ)^{16}O is still not accurately determined; the lower this cross section the higher the temperature of the ^{12}C burning, and therefore the more intense the ν ¯ν emission. With the relatively low ^{12}C(α, γ)^{16}O rates determined both directly from nuclear reactions and from nucleosynthesis by Weaver & Woosley (1993), the entropy carried off during ^{12}C burning in the stars of ZAMS mass ≤ 20 M_⊙ is substantial. The result is rather low-mass Fe cores for these stars, which can evolve into neutron stars. Note that in the literature earlier than Weaver & Woosley (1993) often large ^{12}C(α, γ)^{16}O rates were used, so that the ^{12}C was converted into oxygen and the convective burning did not have time to be effective. Thus its role was not widely appreciated.

Of particular importance is the ZAMS mass at which the convective carbon burning is skipped. In Fig. 2, this occurs at ZAMS mass 19 M_⊙ but with a slightly lower ^{12}C(α, γ)^{16}O rate it might come at 20 M_⊙ or higher. As the progenitor mass increases, it follows from general polytropic arguments that the entropy at a given burning stage increases. At the higher entropies of the more massive stars the density at which burning occurs is lower, because the temperature is almost fixed for a given fuel. Lower densities decrease the rate of the triple-α process which produces ^{12}C relative to the two-body ^{12}C(α, γ)^{16}O which produces oxygen. Therefore, at the higher
entropies in the more massive stars the ratio of $^{12}\text{C}$ to $^{16}\text{O}$ at the end of He burning is lower. The star skips the long convective carbon burning and goes on to the much shorter oxygen burning. Oxygen burning goes via $^{16}\text{O}+^{16}\text{O}$ giving various products, at very much higher temperature than $C(\alpha, \gamma)$ and much faster. Since neutrino cooling during the long carbon-burning phase gets rid of a lot of entropy of the core, skipping this phase leaves the core entropy higher and the final Chandrasekhar core fatter. We believe that our above discussion indicates that single stars in the region of ZAMS masses $\sim 20 - 35\, M_\odot$ end up as high mass black holes.

Arguments have been given that SN 1987A with progenitor ZAMS mass of $\sim 18\, M_\odot$ evolved into a low-mass black hole (Brown & Bethe 1994). We believe from our above arguments that just above the ZAMS mass of $\sim 20\, M_\odot$, single stars go into high-mass black holes without return of matter to the Galaxy. Thus, the region of masses for low-mass black hole formation in single stars is narrow, say $\sim 18 - 20\, M_\odot$ (although we believe it to be much larger in binaries).

3. Quiet Black Hole - Main Sequence Star Binaries

We believe that there are many main sequence stars more massive than the $\lesssim 1\, M_\odot$ we used in our schematic evolution, which end up further away from the black hole and will fill their Roche Lobe during only subgiant or giant stage. From our evolution, we see that a $2\, M_\odot$ main sequence star will end up about twice as far from the black hole as the $1\, M_\odot$, a $3\, M_\odot$ star, three times as far, etc. Two of the 9 systems in our Table 1 have subgiant donors (V404 Cyg and XN Sco). These have the longest periods, 6.5 and 2.6 days and XN Sco is suggested to have a relatively massive donor of $\sim 2\, M_\odot$. It seems clear that these donors sat inside their Roche Lobes until they evolved off the main sequence, and then poured matter onto the black hole once they expanded and filled their Roche Lobe. For a $2\, M_\odot$ star, the evolutionary time is about a percent of the main-sequence time, so the fact that we see two subgiants out of nine transient sources means that many more of these massive donors are sitting quietly well within their Roche Lobes. Indeed, we could estimate from the relative time, that there are $2/9 \times 100 = 22$ times more of these latter quiet main sequence stars in binaries.

4. Discussion

We have shown that it is likely that single stars in the range of ZAMS masses $\sim 20 - 35\, M_\odot$ evolve into high-mass black holes without return of matter to the Galaxy. This results because at mass $\sim 20\, M_\odot$ the convective carbon burning is skipped and this leads to substantially more massive Fe
cores. Even with more realistic reduced mass loss rates on He stars, however, it is unlikely that stars in this mass range in binaries evolve into high-mass black holes, because the progenitor of the compact object when stripped of its hydrogen envelope in either Case A (during main sequence) or Case B (RLOF) mass transfer will burn as a “naked” He star, ending up as an Fe core which is not sufficiently massive to form a high-mass black hole.

In the region of ZAMS mass $\sim 40 \, M_\odot$, depending sensitively on the rate of He-star wind loss, the fate of the single star or the primary in a binary may be a low-mass black hole. In our estimates we have assumed the Brown & Bethe (1994) estimates of $1.5 \, M_\odot$ for maximum neutron star mass and $1.5 - 2.5 \, M_\odot$ for the range in which low-mass black holes can result.

In our evolution of the transient sources using Case C (during He shell burning) mass transfer, almost the entire He core will collapse into a high-mass black hole (Bethe, Brown, & Lee 1999), explaining the more or less common black hole mass of $\sim 7 \, M_\odot$ for these objects, with the possible exception of V404 Cygni where the mass may be greater. Our evolution gives an explanation for the seemingly large gap in black-hole masses, between the $\gtrsim 1.5 \, M_\odot$ for the black hole we believe was formed in 1987A and the $\sim 1.8 \, M_\odot$ black hole we suggest in 1700-37 and the $\sim 7 \, M_\odot$ in the transient sources.

We note that following the removal of the H envelope by Case C mass transfer, the collapse inwards of the He envelope into the developing black hole offers the Collapsar scenario for the most energetic gamma ray bursters of MacFadyen & Woosley (1999).

Acknowledgements

We would like to thank Charles Bailyn and Stan Woosley for useful discussions. We were supported by the U.S. Department of Energy under Grant No. DE–FG02–88ER40388.

References

Bethe, H.A., Brown, G.E., & Lee, C.-H. (1999). ApJ, submitted, astro-ph/9909132
Brown, G.E., & Bethe, H.A. (1994), ApJ, 423, 659
Brown, G.E., Lee, C.-H., & Bethe, H.A. (1999), New Astronomy, 4, 313
De Kool, M., Van den Heuvel, E.P.J., & Pylyser, E. (1987), A&A, 183, 47
Ergma, E., & Van den Heuvel, E.P.J. (1998), A&A, 331, L29
Kaper, L., Lamers, H.J.G.L.M., Van den Heuvel, E.P.J., & Zuiderwijk, E.J. (1995), A&A, 300, 446
MacFadyen, A., & Woosley, S.E. (1999), ApJ, accepted, astro-ph/9810274
Portegies Zwart, S.F., Verbunt, F., & Ergma, E. (1997), A&A, 321, 207
Van den Heuvel, E. P. J., & Habets, G.M.H.J. (1984), Nature, 309, 598
Weaver, T.A., & Woosley, S.E. (1995), Phys. Rept., 227, 65
Wellstein, S., & Langer, N. (1999), A&A, accepted, astro-ph/9904256
Woosley, S.E., & Weaver, T.A. (1995), ApJS, 101, 181