

WHY NS AND BH MASS DISTRIBUTION IS BIMODAL?

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ABSTRACT. The observed mass distribution for the compact remnants of massive stars (neutron stars and black holes) and its relationship to possible mechanisms for the ejection of the envelopes of type II and Ib/c supernovae is analyzed. The conclusion is drawn that this distribution can be obtained only by a magneto-rotational mechanism for the supernovae with sufficiently long time of the field amplification, and a soft equation of state for neutron stars with limiting masses $\sim 1.5\text{--}1.6 M_{\odot}$. Some consequences of this hypothesis are discussed.

Key words: Stars: neutron, black holes, supernova.

1. Introduction

The observed masses of white dwarfs lie in a wide range from several tenths of a solar mass to nearly the Chandrasekhar limit ($\sim 1.2M_{\odot}$), with low-mass white dwarfs encountered more often. We are not concerned with these objects here, and will not consider them further. The masses of neutron stars (NS) measured so far lie within a very narrow interval: the masses for 26 NS radio pulsars in binary systems are consistent with a normal distribution with mean mass $1.35M_{\odot}$ and dispersion $0.04M_{\odot}$ (Thorsett and Chacrabarty 1999). As noted by Thorsett and Chacrabarty, there is currently not a single pulsar in a binary system whose mass exceeds $1.45M_{\odot}$. The recently obtained upper limit on the NS mass in millisecond pulsar PSR J2019+2425 is $M_{\text{NS}} < 1.51 M_{\odot}$ (Nice et al 2001). If we add the less accurately determined masses of NS in X-ray binaries (Cherepashchuk 2000) to this sample, the observed mean mass of NS is $M_{\text{NS}} = (1.35 \pm 0.15) M_{\odot}$ (the same mean as above with a larger dispersion).

More than a dozen of black hole (BH) candidates in close X-ray binary systems are known (see Cherepashchuk (1996, 2000) and references therein). The masses of these objects are determined using radial velocity curves of optical counterparts of binary systems. According to current data, the masses of BH candidates fill the interval $\sim 3\text{--}40 M_{\odot}$, with a mean value of about $10 M_{\odot}$.

In addition to the reliable dynamical determinations

of the NS and BH masses in binary pulsars and X-ray novae, there are a number of less accurate mass estimates for compact objects in X-ray binaries. (1) The mass of NS in the low-mass X-ray binary Cyg X-2 is determined by Orosz and Kuulkers (1999) to be $1.8 \pm 0.2 M_{\odot}$. (2) X-ray pulsar Vela X-1: $M_{\text{NS}} \sim 1.9 M_{\odot}$, according to van Kerkwijk et al (1995), but $M_{\text{NS}} \sim 1.4 M_{\odot}$ according to Stickland et al (1997). (3) The eclipsing low-mass X-ray binary 4U 1700-37: $M_{\text{NS}} = 1.8 \pm 0.4 M_{\odot}$ according to Heap and Corcoran (1992), but it could be a low-mass BH (Brown et al 1996). Until the high masses of these NS are independently verified, we will consider them to be uncertain.

Thus, we assume that current reliable measurements of NS masses lie in a narrow interval $M_{\text{NS}} = (1.35 \pm 0.15) M_{\odot}$, masses of BH lie in a wide range $M_{\text{BH}} > 3M_{\odot}$, and *not a single* NS has currently been reliably detected to have mass in the gap between 1.5 and $3M_{\odot}$, and the number of BH with such small masses is small (the total absence of such BH *is not required*).

This picture is in a dramatic disagreement with both a monotonic distribution of the initial masses of main-sequence stars and the monotonic distribution of masses of carbon and iron cores that are developed during nuclear evolution of massive stars. If a massive star is deprived of its hydrogen envelope during evolution, its carbon core is observed as a Wolf-Rayet star. The current observations show that their masses lie in a wide range from $\sim 3M_{\odot}$ to $\sim 50M_{\odot}$ (Cherepashchuk 2001, 2000, 1998). According to calculations Timmes et al (1996), the masses of the iron cores before collapse lie in the interval from 1.25 to $2.05M_{\odot}$. Both the carbon and iron cores depend monotonically on the initial masses of the stars.

2. The envelope ejection

In sufficiently massive stars ($> 8\text{--}10M_{\odot}$), which can produce NS and BH, the nuclear evolution ends up with the core collapse which can be accompanied by the envelope ejection, leading to the supernova type II or Ib/c. If the shell is ejected "efficiently" (i.e., it receives an energy of the order of the binding energy of the

remnant), it expands in the surrounding medium and a low-mass compact object forms with a mass of order the mass of the collapsed core of the pre-supernova. If the shell is ejected "inefficiently", a large fall of matter from the envelope to the forming compact object is inevitable. As a result, the mass of the latter can substantially grow and approach the pre-supernova mass.

There can be a continuous transition between these two limiting cases. However, if we suppose that *the ejection of the envelope during the supernova explosion is sharply* (even in a step-like manner) *weakened for pre-supernova core masses above some threshold*, the continuous sequence of the pre-supernova masses would give rise to two types of objects with sufficiently different masses.

3. The core collapse

The formation of a compact object during the core collapse can occur in two ways.

(1) The direct collapse into a BH, bypassing an intermediate stage of a hot proto-neutron star, if its mass is above some threshold $M_{dir} > M_{OV}$ (see Prakash et al (2000) and references therein for a more detailed description of this process).

(2) Via the intermediate stage with hot proto-neutron star lasting several seconds or tens of seconds, in which there is intense radiation of thermal energy by the neutrino flux, after which the hot proto-neutron star "cools" or, if its mass exceeds the Oppenheimer-Volkoff limit for neutron star matter M_{OV} , collapses into a black hole.

The modern calculations of core collapses show that $M_{dir} - M_{OV} \approx 0.3-1M_{\odot}$ (Strobel and Weigel (2000) and references therein). Clearly, that for a *static* NS M_{dir} is always larger than M_{OV} .

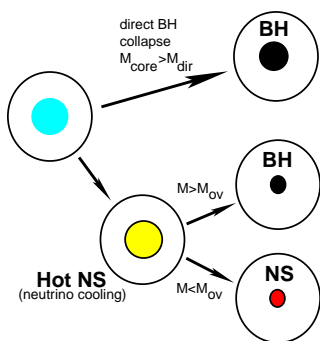


Figure 1: The scheme of the core collapse

The possible ways of the core collapse are schematically shown in Fig. 1.

4. Supernova mechanisms

Let us now consider various mechanisms for super-

nova explosions to find a qualitative shape of the resulting mass distribution of compact objects. The consideration will be based on the illustration with the scheme of Fig. 1 to the left, completed with details of various SN mechanisms, and by the compact mass distribution plot turned counterclockwise to the right.

Excluding exotic models, currently there are three different mechanisms for supernova explosions: (1) The standard mechanism, in which a shock wave appears as a result of the bounce of the matter flux from the "solid" core; the shock wave propagation is sustained by the neutrino flux. (2) The mechanism proposed by Imshennik (1992) is associated with the division of the rapidly rotating collapsing stellar core into two parts. (3) Magneto-rotational mechanism of envelope ejection (Bisnovatyi-Kogan 1970). Let us consider these mechanisms in turn.

Note that none of these mechanisms can presently explain all the facts related to supernova phenomenon. So *a priori* all these mechanism may be equally applicable.

4.1. The standard (neutrino) supernova mechanism

In the standard model, the energy is transferred from the hot compact remnant to the envelope by the neutrino flux. Unfortunately, this mechanism is unable to eject the supernova shell either in the spherically symmetric or the axially symmetric (with rotation) case (Janka 2001). There is some hope that the situation can be saved by large-scale neutrino convection (Herant et al 1994, Mezzacappa et al 1998).

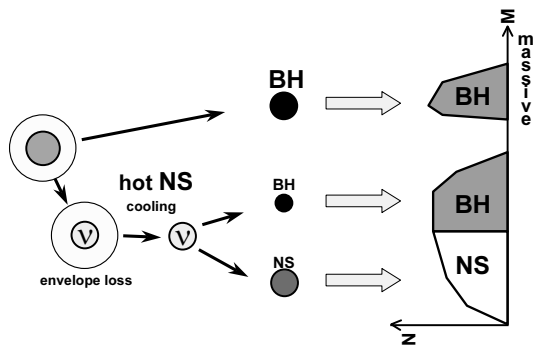


Figure 2: The standard (neutrino) mechanism

The envelope ejection, if any, must occur on the first stage of the hot NS with most intensive neutrino emission (this stage lasts for several seconds). The neutrino fluxes from hot NS with a mass below and above M_{OV} are not strongly different. In a direct collapse, the hot stage is appreciably shorter (of the order of the dynam-

ical time scale for the collapse), and, consequently, is less efficient.

The resulting mass distribution consists of a class of massive BH formed during the direct collapse and a comparable number of NS and low-mass BH (see Fig. 2). This distribution does not match with observations.

4.2. Imshennik's mechanism (the double core)

This mechanism is associated with the division of a rapidly rotating collapsing stellar core into two parts, at least one of which must be a NS. The parts of the binary core then approach due to the emission of gravitational radiation, until the component with the smaller mass (and larger size) fills its Roche lobe. Further, there is an exchange of mass until the mass of the smaller component reaches the lower limit for the mass of a neutron star (about $0.1M_{\odot}$), at which point there is an explosive de-neutronization of the low-mass neutron star. This mechanism was first suggested by Blinnikov et al (1984) and applied to supernova explosions by Imshennik (1992). This additional release of energy fairly far from the center of the collapsing star can efficiently eject its envelope. This mechanism can act only for the most rapidly rotating supernova precursors.

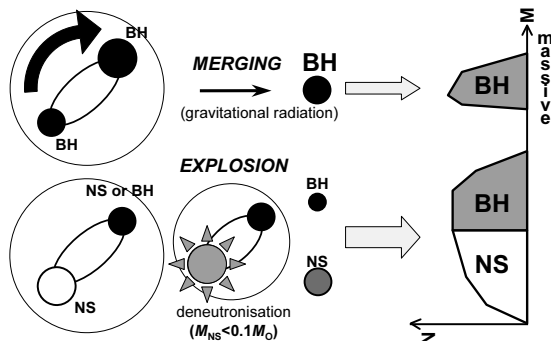


Figure 3: Imshennik's supernova mechanism

The approach of the binary core up to its merging could last from several minutes to several hours; i.e., appreciably longer than the hot neutron star can exist. The scheme of the collapse shown in Fig. 3 is somewhat different: here *massive* is the binary system in which both parts of the core become BH. In this case the process results in a "quiet" coalescence of BH with a concomitant accretion of matter from the envelope.

The processes which take place in the *low-mass* situation are described above and their result is weakly dependent on the mass and type of the compact remnant. As a result, the same mass distribution as for

the neutrino mechanism is obtained, in contradiction with observations.

4.3. Magneto-rotational mechanism

This mechanism was proposed by Bisnovaty-Kogan (1970). The supernova shell is expelled by the magnetic field at the expense of the rotational energy of the newborn NS. The process occurs in two stages. At the first stage, a toroidal magnetic field appears and linearly grows with time. The duration of this stage depends on the NS rotational velocity and its initial magnetic field value and can vary from fraction of a second to hours. When the magnetic field strength approaches some critical value ($\sim 10^{16}$ – 10^{17} G), the magneto-rotational explosion occurs which accelerates and expels the envelope in 0.01–0.1 s (see Ardeljan et al (1998)). For this mechanism to operate, the star should have a sufficiently rapid (but not limiting) rotation.

Depending on the relation between the time of the magnetic field amplification t_B (time before the explosion) and the hot NS cooling time scale t_{ν} , different compact object mass distributions appear.

During the direct core collapse into BH, the magnetic field amplification never starts and the envelope are not ejected. In contrast, on the branch leading to NS formation, the magneto-rotational mechanism ultimately leads to the explosion and the envelope ejection.

The difference between the two variants concerns only objects with masses $M_{OV} < M < M_{dir}$, in which initially a hot NS forms and after cooling collapses into BH. If the explosion occurs at the stage of a hot NS ($t_B < t_{\nu}$), the envelope is ejected before stars with $M > M_{OV}$ collapse; they form low-massive BH. Therefore, we for the third time obtain the mass distribution in disagreement with observations.

In contrast, if the field amplification proceeds slowly ($t_B > t_{\nu}$), the objects with $M_{OV} < M < M_{dir}$ collapse into BH, after which the field amplification stops. No magneto-rotational explosion, and hence, envelope ejection occurs, so masses of these BH will be weakly different from those formed during the direct collapse. The mass distribution will consist of only two groups of objects: NS and massive BH.

Note one very important corollary of the scheme considered: the upper boundary of the NS mass distribution must coincide (to the mass defect) with M_{OV} . Thus the current observations suggest that NS should have a *very soft* EOS with $M_{OV} \simeq 1.5$ – $1.6M_{\odot}$ (such equation are possible, e.g. GS1, PAL6 and PCL2 in Lattimer and Prakash (2000)).

The magneto-rotational explosion is illustrated in Fig. 4.

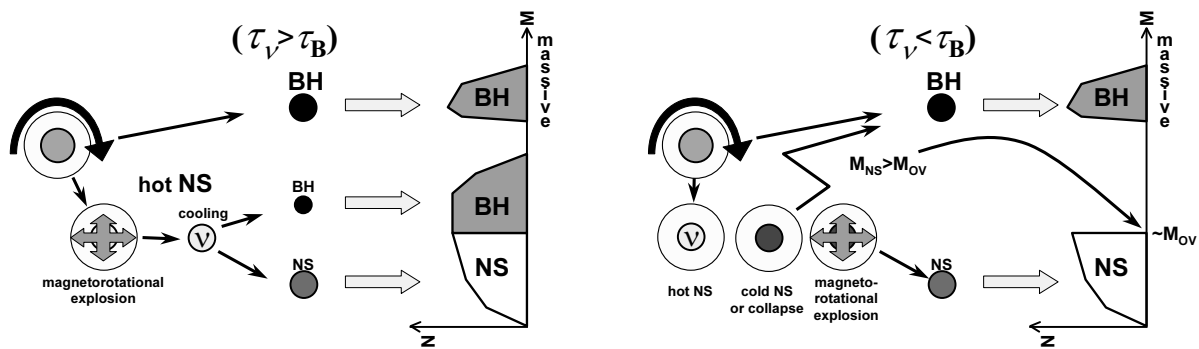


Figure 4: Two ways of the magneto-rotational mechanism for SN explosion

5. Conclusions

We have shown that the magneto-rotational mechanism for supernova explosions, with the additional requirements that the time before the explosion is larger than the cooling time of a proto-NS ($\tau_B > \tau_\nu$) with a soft equation of state of NS matter ($M_{OV} \simeq 1.5\text{--}1.6 M_\odot$), leads naturally to the mass distribution of compact objects similar to what is currently observed. To eject the envelope, the NS rotational energy should be above $\sim 10^{50}$ ergs (period of rotation < 10 ms). Unless the magnetic coupling between the pre-collapse core and envelope is strong enough to preclude rapid rotation of the core, as was suggested in Spruit and Phinney (1998), the magneto-rotational supernova explosion is very attractive mechanism. This hypothesis has a number of additional predictions, which can be verified by observations:

(1) Accretion-induced BH with masses of about M_{OV} should exist. They could be detected in low-mass transient X-ray binaries.

(2) Supernova remnants containing BH must be less energetic evidencing less energetic supernova explosions. Supernova remnants with NS should be axially symmetric.

(3) The coaxiality of the angular momentum and the space velocity of a pulsar, as observed in Crab and Vela pulsars, must be a common property of all radiopulsars.

(4) BH should have very small space velocities in comparison with pulsars.

Reliable measurements of the NS mass substantially above $1.6 M_\odot$ would be a *direct refutation of the proposed hypothesis*.

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