

# Measuring the Masses of Neutron Stars

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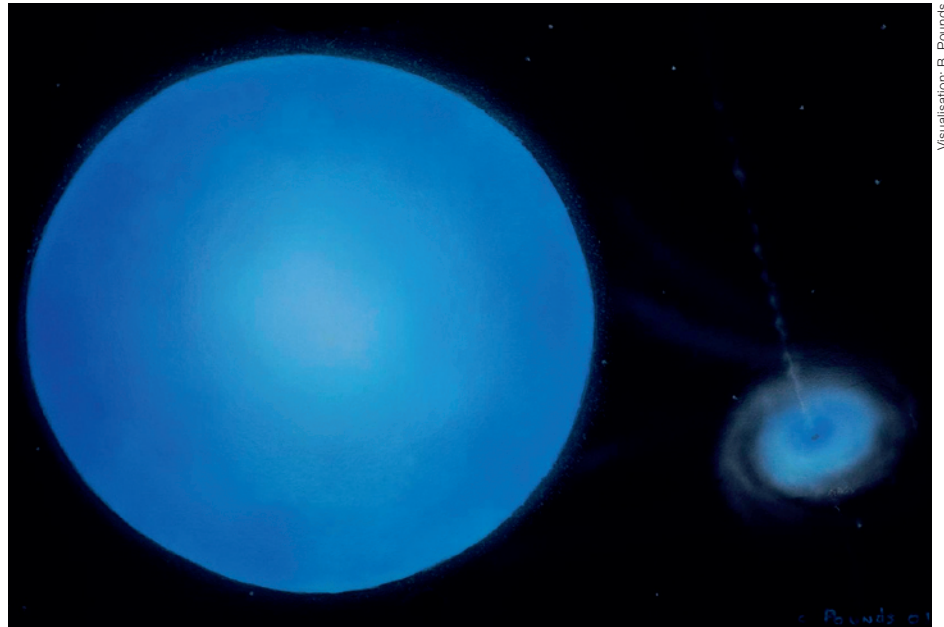
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Until a few years ago the common understanding was that neutron stars, the compact remnants of massive stars, have a canonical mass of about  $1.4 M_{\odot}$ . Recent observations with VLT/UVES support the view that the neutron stars in high-mass X-ray binaries display a relatively large spread in mass, ranging from the theoretical lower mass limit of  $1 M_{\odot}$  up to over  $2 M_{\odot}$ . Such a mass distribution provides important information on the formation mechanism of neutron stars (i.e. the supernovae), and on the (unknown) behaviour of matter at supranuclear densities.

## The compact remnants of massive stars

A neutron star is the compact remnant of a massive star ( $M \geq 8 M_{\odot}$ ) with a central density that can be as high as 5 to 10 times the density of an atomic nucleus. Neutron stars can be detected as radio sources (radio pulsars) or, when they accrete matter coming from a companion star in a binary system, as X-ray sources.

The global structure of a neutron star depends on the equation of state (EOS), i.e. the relation between pressure and density in the neutron star interior (Lattimer and Prakash 2004). So far, the physical properties of matter under these extreme conditions can only be studied on the basis of theoretical models. It is not yet possible to produce the required extremely high density in accelerator experiments. Given an EOS, a mass-radius relation for the neutron star and a corresponding maximum neutron-star mass can be derived. The ‘stiffness’ of the EOS depends e.g. on how many bosons are present in mat-



Visualisation: B. Pounds

ter of such a high density. As bosons do not contribute to the fermi pressure<sup>1</sup>, their presence will tend to ‘soften’ the EOS. For a soft EOS, the maximum neutron star mass will be low ( $\sim 1.5 M_{\odot}$ ); for a higher mass, the object would collapse into a black hole. More than 100 candidate equations of state are proposed, but only one EOS can be the correct one. Finding one massive neutron star ( $M \geq 2 M_{\odot}$ ) would rule out the soft equations of state.

The measurement of neutron-star masses is thus important for our understanding of the EOS of matter at supranuclear densities. In practice, this can only be done for neutron stars in binary systems. The most accurate masses have been derived for the binary radio pulsars. Until recently, all of these were consistent with a small mass range near  $1.35 M_{\odot}$  (Thorsett and Chakrabarty 1999). An exception is the X-ray pulsar Vela X-1 with a mass of  $1.86 \pm 0.16 M_{\odot}$  (Barziv et al. 2001). This important result was obtained following a nine-month spectroscopic monitoring campaign with the ESO *Coudé Auxiliary Telescope* and the CES spectrograph, covering 36 orbits of the binary system. Over the past year a few more massive neutron stars were discovered, e.g. the millisecond radio pulsar J0751+

Figure 1: Artist's impression of a high-mass X-ray binary hosting a massive OB-type star and a compact X-ray source, a neutron star or a black hole.

1807 with a mass of  $2.1 \pm 0.2 M_{\odot}$  (Nice et al. 2005). These results favour a stiff EOS.

A neutron star cannot be more massive than  $3.2 M_{\odot}$ , a limit set by general relativity. It is likely that the maximum neutron-star mass is determined by the stiffness of the EOS, and is expected to be about  $2.5 M_{\odot}$ . Neutron stars also have a minimum mass limit. The minimum stable neutron-star mass is about  $0.1 M_{\odot}$ , although a more realistic minimum stems from a neutron star's origin in a supernova. Lepton-rich proto neutron stars are unbound if their masses are less than about  $1 M_{\odot}$  (Lattimer and Prakash 2004). Whether or not neutron stars occupy the full available mass range depends on the formation mechanism, i.e. the supernova.

We focus here on the initially most massive binary systems<sup>2</sup>, which consist of a massive OB-supergiant and a neutron star (or a black hole). The main motivation to concentrate on these systems is that they are the most likely hosts of massive neutron stars. About a dozen of these systems are known; five of them

<sup>1</sup> The repelling force that neutrons (fermions) exert on each other so that a neutron star can sustain gravity.

<sup>2</sup> About 80% of the HMXBs are Be/X-ray binaries, where the (transient) X-ray source accretes material from the equatorial disc around a Be star.

contain an eclipsing X-ray pulsar. The masses of all but one (Vela X-1) are consistent (within their errors) with a value of about  $1.4 M_{\odot}$ . However, most spectroscopic observations used for these mass determinations were carried out more than 20 years ago, before the advent of sensitive CCD detectors and 8-m-class telescopes, which allow high-resolution spectroscopy of the optical companions. The uncertainties in the earlier radial velocity measurements are too large to measure a significant spread in mass among these neutron stars, if present.

### High-mass X-ray binaries

High-mass X-ray binaries (HMXBs) represent an important phase in the evolution of massive binaries. They are composed of a massive OB-type star and a compact object, either a neutron star or a black hole (Figure 1). The X-ray source is powered by accretion of material originating from the OB star, transported by the OB-star wind or by Roche-lobe overflow. About a dozen HMXBs are known to host a massive OB-supergiant companion (about 10 to over  $40 M_{\odot}$ ), in a relatively tight orbit ( $P_{\text{orb}}$  several days) with an X-ray pulsar or black-hole companion (Table 1). Some of these X-ray binaries include a dense accretion disc and produce relativistic jets. Recently, several new sources have been discovered with the ESA gamma- and hard-X-ray observatory INTEGRAL that show the characteristics of a HMXB with an OB-supergiant companion hidden by large amounts of interstellar dust (e.g. Negueruela et al. 2005); these are not included in the table.

The compact companion is the remnant of the initially most massive star in the system that exploded as a supernova. Due to a phase of mass transfer, the secondary became the most massive star in the system before the primary supernova, so that the system remained bound. A consequence, however, is that HMXBs are runaways due to the kick velocity exerted by the supernova (Blaauw 1961). When they run through space with supersonic velocity, the interaction of the OB-supergiant wind with the interstellar medium can result in the formation of a bow shock (see also The Messenger 89, 28).

The HMXB phase is relatively short for OB-supergiant systems, of the order of 10 000 years. This corresponds to the time required for the secondary to evolve into a supergiant when the hydrogen in the nucleus has been exhausted. As soon as the secondary has become an OB-supergiant it develops a strong stellar wind. The accretion of wind material turns the compact object into an observable X-ray source. Once the supergiant starts to overflow its Roche lobe, the mass transfer rate increases further so that an accretion disc is formed around the compact object, turning it into a very strong X-ray source accreting at the Eddington limit. Soon after, the increasing mass transfer rate causes the system to enter a phase of common-envelope evolution swamping the X-ray source and finally causing the compact object to spiral into the OB-supergiant.

From this stage on the evolution of the system can proceed in different ways, depending on the orbital separation. In the relatively wide Be/X-ray binaries the

spiral-in likely results in the removal of the envelope of the Be companion, and after the (second) supernova a bound (or disrupted) double neutron star remains, like the Hulse-Taylor binary pulsar PSR 1913+16 (or a neutron star – white dwarf system, if the mass of the Be companion is less than  $8 M_{\odot}$ ). In HMXBs with an orbital period less than about a year the compact object will enter the core of the OB companion which will become a Thorne-Zytkow object, a red supergiant with a high mass loss rate. These objects have been predicted on evolutionary grounds, but have so far not been recognised as such.

Table 1 lists the basic properties of the HMXBs with OB-supergiant companions in the Milky Way and the Magellanic Clouds. Most sources contain an X-ray pulsar; the pulse period (i.e. rotation period of the neutron star) is short and the X-ray luminosity high ( $L_X \sim 10^{38}$  erg s<sup>-1</sup>) in systems undergoing Roche-lobe overflow due to the higher mass- and angular-momentum accretion rate. The latter systems also have circular orbits, while the wind-fed systems have eccentricities up to  $e = 0.45$  (GX301-2, Kaper et al. 2006) and an X-ray luminosity  $L_X \sim 10^{35} - 10^{36}$  erg s<sup>-1</sup>.

### Neutron stars versus black holes

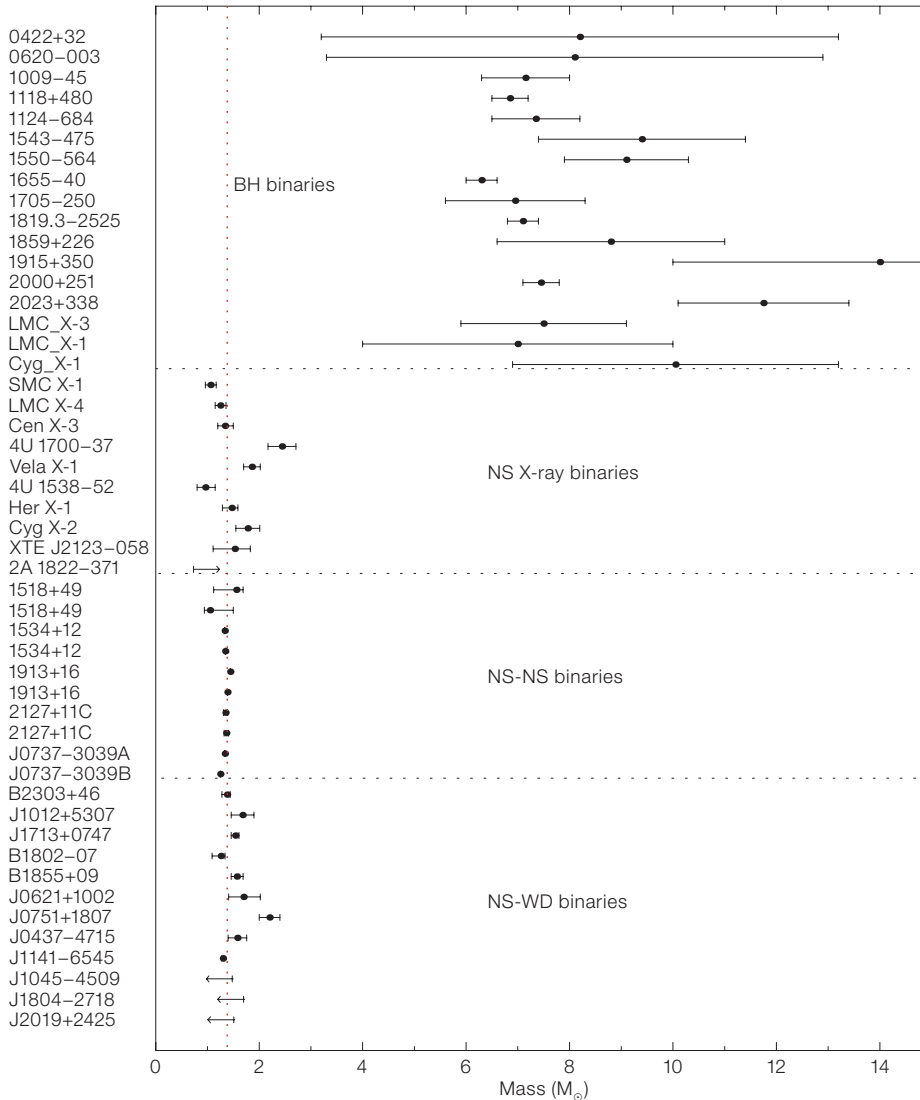
In Figure 2 the mass distribution of neutron stars and black holes is shown, based on measurements collected from the literature (Stairs 2004, McClintock and Remillard 2005). The neutron stars occupy a relatively narrow mass range near  $1.4 M_{\odot}$ . The most accurate neutron-

Name	Spectral Type	$M_{\text{OB}} (M_{\odot})$	$M_X (M_{\odot})$	$P_{\text{orb}} (d)$	$P_{\text{pulse}} (d)$
2S0114+650	B1 Ia	$16 \pm 5$	$1.7 \pm 0.5$	11.6	860
SMC X-1	B0 Ib	$15.7 \pm 1.5$	$1.06 \pm 0.11$	3.89	0.71
LMC X-4	O7 III–IV	$14.5 \pm 1.0$	$1.25 \pm 0.11$	1.40	13.5
Vela X-1	B0.5 Ib	$23.8 \pm 2.4$	$1.86 \pm 0.16$	8.96	283
Cen X-3	O6.5 II–III	$20.2 \pm 1.8$	$1.34 \pm 0.16$	2.09	4.84
GX301-2	B1.5 Ia+	$40 \pm 10$	$1.9 \pm 0.6$	41.5	696
4U1538-52	B0 Iab	$16 \pm 5$	$1.1 \pm 0.4$	3.73	529
4U1700-37	O6.5 Iaf+	$58 \pm 11$	$2.4 \pm 0.3$	3.41	
4U1907+09	early B I	$\sim 27$	$\sim 1.4$	8.38	438
LMC X-3	B3 ve	$\sim 6$	6–9	1.70	
LMC X-1	O7-9 III	$\sim 20$	4–10	4.22	
LS5039	O6.5 v((f))	20–35	$1.4 \pm 0.4$	4.43	
SS433	A3-7 I	$11 \pm 3$	$2.9 \pm 0.7$	13.08	
Cyg X-1	O9.7 Iab	$18 \pm 6$	$10 \pm 5$	5.60	

**Table 1:** High-mass X-ray binaries with OB-supergiant companion in the Milky Way and the Magellanic Clouds (ordered according to right ascension). The name corresponds to the X-ray source, the spectral type to the OB-supergiant. For the systems hosting an X-ray pulsar the masses of both binary components can be measured (given an estimate of the inclination of the system). The last five systems most likely contain a black-hole candidate; for the Galactic sources among them relativistic jets have been detected.

**Figure 2:** Neutron-star and black-hole masses obtained from the literature (Stairs 2004, McClintock and Remillard 2005, and references therein). The neutron stars, especially the binary radio pulsars (at the bottom), occupy a relatively narrow mass range near  $1.35 M_{\odot}$ . The X-ray pulsars (to the middle)

show a wider spread, including two systems with a neutron-star mass near  $2 M_{\odot}$ . Such a high neutron-star mass would rule out a soft equation of state. The black-hole candidates (at the top) are significantly more massive, indicative of a different formation mechanism.



star masses have been derived for the binary radio pulsars (NS-NS binaries), with an average mass of  $1.35 \pm 0.04 M_{\odot}$  (Thorsett and Chakrabarty 1999). The X-ray pulsars (NS-X-ray binaries) show a somewhat larger mass range, extending both below and above  $1.35 M_{\odot}$ . Besides Vela X-1, also a high mass is claimed for the system 4U1700-37 ( $2.4 \pm 0.3 M_{\odot}$ , Clark et al. 2002), although the X-ray source is, contrary to Vela X-1, not an X-ray pulsar (and perhaps a low-mass black hole).

The estimated masses of black-hole candidates are substantially larger ( $8.4 \pm 2.0 M_{\odot}$ ) than those measured for neutron stars. This suggests that neutron stars and black holes are formed in different

ways. If, for example, black holes are the result of ‘failed’ supernovae in which the stellar mantle is not blown away, but accretes onto the compact remnant, one would expect a significant difference in mass between neutron stars and black holes. However, if the mass of the (proto) neutron star is increased by the fall back of material which was located outside the collapsing degenerate Fe core of the exploding star, one would predict that neutron stars would occupy a range in mass, up to the maximum neutron-star mass allowed by the equation of state. Certainly in the binary radio pulsars such a mass distribution is not observed. With the recent evidence that a black hole may be formed during the collapse of a massive star in a gamma-ray burst (see,

e.g., The Messenger 109, 37, and this issue, page 16) the hypothesis would be that neutron stars are formed in ‘ordinary’ supernovae, while black holes originate in gamma-ray bursts.

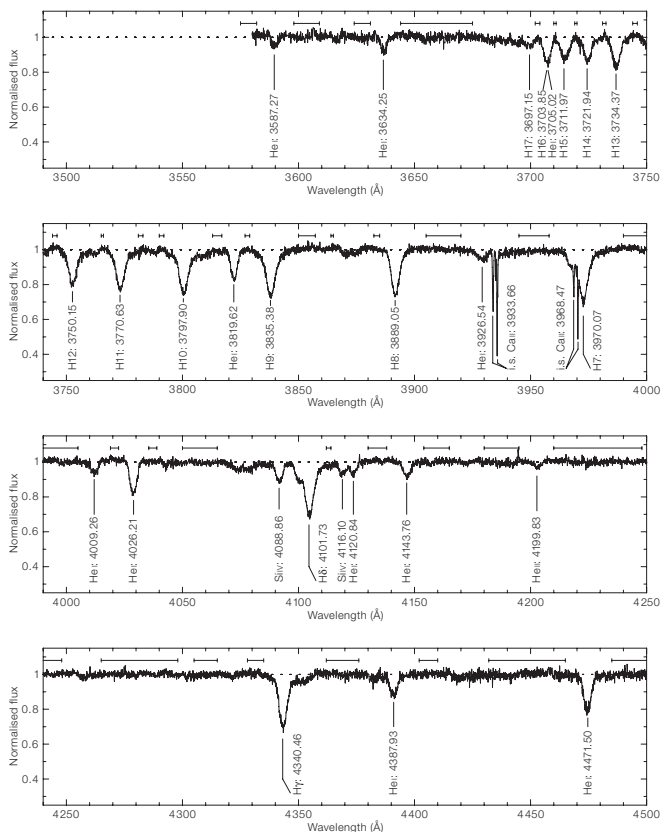
### VLT/UVES observations

If the HMXB hosts an X-ray pulsar, its orbit can be very accurately determined through pulse-timing analysis. When the radial-velocity curve of the OB-supergiant is also obtained, the mass of the neutron star and that of the massive star can be derived with precision, given an estimate of the system inclination. In systems showing an X-ray eclipse the inclination must be larger than  $i \sim 65^{\circ}$ . For Roche-lobe overflow systems a valid assumption is that the OB-supergiant is in corotation with the orbit, which provides a strong constraint on the system inclination.

Van der Meer et al. (2006) have analysed the radial-velocity curves of the three known OB-supergiant systems with an (eclipsing) X-ray pulsar undergoing Roche-lobe overflow. These systems are Cen X-3, the first detected binary X-ray pulsar (Giacconi et al. 1971) in the Milky Way; LMC X-4 in the Large Magellanic Cloud; and SMC X-1 in the Small Magellanic Cloud. The OB-supergiant counterparts to these X-ray pulsars have  $V$  magnitudes in the range 13–14. Other properties of these systems are listed in Table 1. High spectral resolution ( $R \sim 40000$ ) and high signal-to-noise spectra of these systems have been obtained with VLT/UVES, covering 12 epochs evenly spread over the (circular) orbit of the system.

To obtain a radial-velocity measurement, often the complete spectra are cross correlated with a template spectrum. This approach has many advantages when using spectra with relatively low spectral resolution and poor signal to noise. In our case the spectra are of such high quality (Figure 3) that the radial-velocity amplitude can be determined for each line separately (Figure 4). The advantage of such a strategy is that it is possible to assess the influence of possible distortions due to e.g. X-ray heating and gravity darkening, as in these systems the

**Figure 3:** Blue VLT/UVES spectrum of the B-supergiant companion to the X-ray pulsar SMC X-1. The hydrogen and helium lines characteristic of early-type star spectra are indicated. The spectral lines move back and forth due to the orbital motion of the star (from Van der Meer et al. 2006).



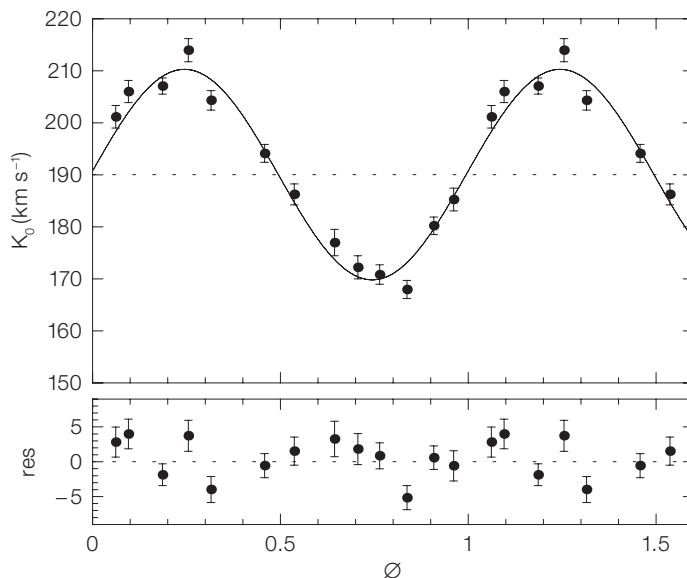
OB-star is irradiated by a powerful X-ray source and is filling its Roche lobe. For more details on the applied methods we refer to Van der Meer et al. (2006).

The resulting masses are  $1.06 \pm 0.11 M_{\odot}$  for SMC X-1,  $1.25 \pm 0.10 M_{\odot}$  for LMC X-4, and  $1.34 \pm 0.16 M_{\odot}$  for Cen X-3 (at a  $1\sigma$  confidence level), i.e. an improvement in accuracy by at least a factor of two. Whereas some HMXBs have shown to host a neutron star with a mass higher than  $1.4 M_{\odot}$ , as is the case for Vela X-1 and possibly 4U1700-37, the mass of SMC X-1 is low, just above the minimum neutron-star mass of  $\sim 1 M_{\odot}$ , and significantly different from the mass of Vela X-1. We thus conclude that the neutron stars in HMXBs have different masses, i.e. they do not all have the same canonical mass.

The three studied systems do not host a massive neutron star. Following the hypothesis that the mass of the compact remnant depends on the mass of the progenitor star, one would conclude that the progenitors of the neutron stars in these systems had a relatively low mass, especially the progenitor of SMC X-1

( $M \leq 14 M_{\odot}$ ). A reconstruction of the evolutionary history of this binary system shows that this is possible (Van der Meer et al. 2006). Initially, the system would have contained a  $13 M_{\odot}$  and a  $9 M_{\odot}$  star. The nuclear burning rate of the  $13 M_{\odot}$  star is fastest, so that it will have reached the end of nuclear hydrogen burning first. When it starts to become a supergiant, it starts overflowing its Roche lobe, so that the companion  $9 M_{\odot}$  star will receive mass and becomes a  $16 M_{\odot}$  star (i.e. the current mass of the B supergiant companion to SMC X-1, neglecting the mass that the supergiant has lost due to its stellar wind). The current short orbital period of the system (3.89 d) indicates that during this process of mass transfer the system must have lost angular momentum (otherwise the orbit would have become much wider), but not much mass.

Our current hypothesis is that the lowest-mass neutron star (e.g. SMC X-1) is the end product of a massive star in the range of about  $8$  to  $14 M_{\odot}$  (stars with a mass less than  $8 M_{\odot}$  do not explode as a supernova). Neutron stars with a mass



**Figure 4:** Radial-velocity curve of the B-supergiant companion to SMC X-1 based on the measurement of a single line (hydrogen Balmer 2–10). The resulting radial-velocity amplitude of the B supergiant is  $20.2 \pm 1.2 \text{ km s}^{-1}$ . Combined with the mass function of the X-ray pulsar and the system inclination of  $67 \pm 5$  degrees a neutron star mass of  $1.06 \pm 0.1 M_{\odot}$  is obtained. This makes SMC X-1 the lowest mass neutron star known (from Van der Meer et al. 2006).

near  $1.3 M_{\odot}$  are produced by progenitors in the range  $14$  to  $19 M_{\odot}$ . The most massive neutron stars, like Vela X-1, come from stars with an initial mass higher than  $19 M_{\odot}$ . The apparent lack of low-mass black holes ( $M \sim 3 M_{\odot}$ ) suggests that black holes are formed by a different mechanism than neutron stars, e.g. a gamma-ray burst rather than a supernova.

#### Acknowledgement

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