NEWS AND VIEWS

The Supernova-Black Hole Connection

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Black holes have long been regarded as mysterious or exotic objects. While increasing observational evidence supports their existence, there have been continuing questions about how these objects form. In one possible scenario a massive (more than 25 x the mass of the sun, $M_{\odot}$) star collapses due to its large gravitational mass. An alternative, more complicated model proposes that a massive star first undergoes a supernova explosion during which some of the ejected material from the exploding star falls back onto a newly-born neutron star, which subsequently collapses to form a black hole (see Figure 1). Recent observational work by Israelian *et al.*[1] to appear in *Nature* has shed new light on the formation of these exotic objects and suggests the latter scenario is correct, at least for one black hole.

The search for black holes has primarily relied upon determining the gravitational masses of the (unseen) companions of stars in binary star systems. The strong gravitational attraction of the black hole, in systems where the stars are physically close, results in material being pulled off the companion (or secondary) star. As the matter is accreted by the black hole, it forms a disk with high temperatures near, but outside of the black hole. This high temperature gas occasionally produces X-ray emission. The mass of the secondary star can be determined from its observed properties. Observations of the periodic Doppler shifts of the orbiting secondary star allow the estimation of the mass of the compact object, which may be a black hole. Masses in excess of 3 $M_{\odot}$ are a clear indication of the presence of a black hole. The sun and the vast majority of all stars will end their lives as white dwarfs with masses $\leq$ 1.4 $M_{\odot}$. Neutron stars which are the remnants of relatively rare supernovae – the total rate for all supernovae is estimated to be one per 100 years in our Galaxy - have a maximum estimated mass[2] of less than 3 $M_{\odot}$.

One such X-ray binary, detected by the *Compton Gamma Ray Observatory*, is GRO J1655-40 also known as Nova Scorpii 1994. It contains a black hole with an estimated mass of 5.5–7.9 $M_\odot$ and a subgiant (*i.e.*, evolved) companion star with a mass[3,4] of 1.7–3.3 $M_\odot$. Israelian *et al.* observed Nova Scorpii 1994 during a quiescent X-ray phase using the high-resolution spectrograph (HIRES) of the 10m Keck telescope. They were able to determine the abundances of a number of heavy elements, and specifically O, Mg, Si and S, in the visible, secondary star in Nova Scorpii 1994, and found those abundances to be 6–10 times higher than in the sun. This enhancement is particularly significant, since these so called α-elements, composed of ^{4}He nuclei or alpha particles cannot have been produced, in such quantities, internally in the observed star. Instead, these elements are primarily synthesized in explosive nuclear processing in the very last stages of the evolution and in the interior regions of massive stars that will explode as Type II, Ib or Ic (also known as core-collapse) supernovae. The major products of explosive oxygen burning in such objects are ^{16}O, ^{28}Si, ^{32}S, ^{36}Ar and ^{40}Ca, and are synthesized in the innermost regions of these 25–40 $M_\odot$ massive stars at temperatures in excess of 3 billion K on timescales of seconds.[5] The vast majority of stars, normal low-mass stars such as the sun, will never achieve such temperatures during their lifetimes and therefore are unable to synthesize the α-elements.

While there might be other possibilities, the most logical explanation for the observed enhanced abundances of these α-elements in the secondary star in Nova Scorpii 1994, and the one proposed by Israelian *et al.*, is that they are the result of the supernova explosion of the original primary star in this system. What is still not clear is why the supernova explosion did not disrupt or remove parts of the stellar atmosphere of the companion star. Nor is it clear exactly how the α-element-rich supernova ejecta were actually captured and retained by the atmosphere of the companion.

Predictions[1] of the initial mass of the supernova progenitor, based upon the lack of the binary's disruption during the explosion, are again consistent with stellar evolution models[5] of stars from 25–40 $M_\odot$. The predicted nucleosynthetic yields of the α-rich elements from explosive processing in stars of this same mass range are also consistent with the observed abundances in Nova Scorpii 1994. In addition to ejecting at least several solar masses of processed nucleosynthetic material rich in α-elements, some stars in this mass range might also form black holes.[6] During the explosion a certain amount of the ejected material will "fall back" onto the newly formed neutron star, that is normally produced in these Type II supernovae. If the amount of fall-back matter pushes the mass of the neutron-star above 3 $M_\odot$, it will collapse to a black hole on a timescale of seconds to hours, a scenario that seems to characterize what occurred in Nova Scorpii 1994. The timescale for that black hole formation can also be estimated. The fact that the α-element abundances were still detectable in the companion star suggests that only a small fraction of its mass could have been transferred to the black hole. Mass-loss rates in typical X-ray binaries suggest that the black hole in GRO J1655-40 formed less than one million years ago and has not increased in mass significantly during that time.

There are, of course, still a number of unanswered questions. Is the formation history of the black hole in GRO J1655-40 typical? What fraction of black holes first go through an intermediate supernova stage? Do, for example, stars more massive than 40 $M_\odot$ directly collapse to form black holes? Are there also cases where both a black hole and a supernova form simultaneously? Can we detect the presence of the α-elements, the signature of the Type II supernova explosion, in black hole companions in other X-ray binary systems (Cygnus X-1, for example)? If so, can we then use those observations to understand more about the details of element formation in these supernova explosions? While clearly many more observations will be needed to answer those questions, we now have the first convincing evidence that at least some black holes first form as supernovae.

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[2] Kalogera, V. & Baym, G. *Astrophys. J.* **470**, L61-64 (1996).

[3] Orosz, J. & Bailyn, C. *Astrophys. J.* **477**, 876-896 (1997).

[4] Shabaz, et al. *Monthly Not. Royal Astron. Soc.* **306**, 89-94 (1999).

[5] Thielemann, F.-K., Nomoto, K. & Hashimoto, M. *Astrophys. J.* **460**, 408-436 (1996).

[6] Woosley, S. & Weaver, T. *Astrophys. J. Suppl.* **101**, 181-235 (1995).