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Core-collapse supernovae and evidence for black hole formation

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Abstract. A group of core-collapse supernovae show remarkably peculiar properties, such as an extremely low expansion velocity and an extraordinary small amount of Nickel in the ejecta. They may originate from high mass progenitors undergoing a low energy explosion with the formation of a black hole.

Key words. black holes – stars: supernovae: general

1. Introduction

The theoretical scenario for the formation of neutron stars and solar-mass black holes (BHs) envisages the collapse of the core during the late evolutionary stages of massive ($> 8\,\mathrm{M}_\odot$) stars. The discovery of radio pulsars in supernova (SN) remnants proved that neutron stars are indeed formed in SN explosions, but similar evidence for the presence of solar-mass BHs in the site of their formation is still lacking. Although recent observations of an overabundance of Nitrogen and Oxygen in the atmosphere of the companion star in the BH binary system GRO J1655-40 support indirectly the BH-forming SN scenario (Israelian et al. 1999), a convincing direct proof of the formation of BHs in SNe or of their presence in SN remnants has not been gathered as yet. In fact, until recently it has been difficult even to identify core-collapse SNe occurring in high mass progenitors whose properties are suitable for BH formation. Recent progress both on the theoretical and observational side have improved significantly our understanding in this area.

2. Core-collapse and BH formation

The spectacular optical display of a SN originates from the gravitational potential energy liberated by the sudden collapse of the core at the end of the life of a massive

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star. This energy is deposited in part in the stellar envelope by the shock wave formed at core-bounce and later revived by neutrino reheating and/or complex magnetohydrodynamical processes. While the mass of the iron core and hence the gravitational potential energy liberated during the collapse are roughly independent of the progenitor mass M_* (Woosley & Weaver 1995), the total binding energy of the stellar envelope tends to increase rapidly with M_*. Furthermore, the lack of internal pressure support after core collapse causes an early accretion of gas from the base of the envelope that becomes progressively more important as M_* increases (Fryer 1999). A lot of energy is spent in order for the delayed shock to overcome the binding energy of the envelope and the ram pressure of the infalling stellar material. This has the effect to decrease the energy available to heat up and accelerate the envelope. Thus, in a massive progenitor a variable amount of matter may remain gravitationally bound to the collapsed remnant after the explosion. This stellar material may both turn the newly formed neutron star into a BH and fuel an ongoing accretion flow onto the central remnant (*fallback*). If a BH forms, the late time fallback may give rise to detectable emission of radiation with a characteristic and persistent *power-law decay* with time (Zampieri et al. 1998; Balberg et al. 2000), that must eventually dominate over the *exponentially decaying* power from radioactive heating. Its detection in the late time light curve would provide the first direct evidence for the presence of a BH in the site of its formation. Recently, a number of Type II events with remarkably peculiar properties have been discovered (Pastorello et al. 2003). The first clearly identified example was the exceptionally faint SN 1997D in NGC 1536 (Turatto et al. 1998; Benetti et al. 2001). SN 1997D showed both a very faint radioactive tail in the light curve, corresponding to an ejected ^{56}Ni mass ~ 0.005 M$_\odot$, and a very small expansion velocity ~ 1000 km s^{-1}. Turatto et al. (1998) pointed out that this SN could have originated in the low energy explosion of a massive progenitor and that it could host a BH. However, SN 1997D was discovered at the end of the plateau stage when the light curve was plummeting, and then the estimate of the explosion epoch was uncertain. New spectral and photometric data of recent low luminosity events, as SN 1999br, allowed us to obtain a more accurate phase calibration of the explosion. Using these data, we performed a new analysis of SN 1997D and other low luminosity SNe and found that the parameters of the ejecta are consistent with them being at least intermediate mass core-collapse events undergoing a low energy explosion (Zampieri et al. 2003). This suggests that they may form a BH, giving rise to significant fallback and late-time accretion. In fact, while in a typical Type II SN the fallback luminosity is too low to be detectable, in 97D-like events conditions are much more favourable for detection of the BH accretion luminosity. Emerge of the BH is expected at ~ 1000 days after the explosion (Zampieri et al. 1998b; Balberg et al. 2000). Therefore, late time (2–3 years) observations of low luminosity Type II SNe are of fundamental importance to detect the BH accretion luminosity fuelled by the stellar envelope. The potential of detecting this characteristic emission represents an exciting new prospect for identifying BHs in the site of their formation and confirm our theories of BH formation.

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