LETTERS

A runaway collision in a young star cluster as the origin of the brightest supernova

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Supernova SN 2006gy in the galaxy NGC 1260 is the most luminous recorded[1–4]. Its progenitor might have been a very massive ($>100M_\odot$, where $M_\odot$ is the mass of the Sun) star[5], but that interpretation is incompatible with hydrogen in the spectrum of the supernova; stars $>40M_\odot$ are believed to have shed their hydrogen envelopes several hundred thousand years before the explosion[6]. Alternatively, the progenitor might have arisen from the merger of two massive stars[7]. Here we show that the collision frequency of massive stars in a dense and young cluster (of the kind to be expected near the centre of a galaxy) is sufficient to provide a reasonable chance that SN 2006gy resulted from such a bombardment. If this is the correct explanation, then we predict that when the supernova fades (in a year or so) a dense cluster of massive stars will become visible at the site of the explosion.

The presence of hydrogen in SN 2006gy is hard to reconcile with the explosion of a $\gtrsim 40M_\odot$ star, because such a star loses its hydrogen-rich envelope several hundreds of thousands of years before the star explodes[6]. Also, the location of the supernova, at a projected distance of about 1$''$ ($\sim$350 parsecs, pc) from the nucleus of the host galaxy NGC 1260, is remarkable. A merger between a very massive ($>100M_\odot$) hydrogen-depleted star (that already had a core in an advanced phase of helium burning) and a hydrogen-rich main-sequence star of 10–$40M_\odot$ that occurred 10^4 to 10^5 years before the supernova explosion may explain the unusual brightness of the supernova, the presence of the hydrogen in the interstellar medium surrounding the supernova and the presence of hydrogen in the supernova itself[5,7].

The existence of young star clusters that are in a state of dynamical core collapse is crucial for the proposed scenario. During core collapse and the subsequent post-core-collapse evolution of the star cluster, a runaway collision product can grow[8], and even though the star is likely to be much more extended than usual, subsequent bombardment will result in a net increase in mass[9]. Eventually the massive star is expected to prostrate to a black hole of intermediate mass[10,11]. The supernova in which the black hole forms is likely to be unusually bright with some hydrogen in its envelope leftover from the last collision.

The inner few hundred parsecs around the centre of the Milky Way is populated with several bright and dense star clusters, of which the Arches cluster[12] and Quintuplet[13] are the most well known, but many others exist[14–16]. The proximity of the Galactic centre and the depth of the potential well of the bulge causes these clusters to be denser than elsewhere in the Galaxy[17].

The SB/SB0 host galaxy NGC 1260 appears rather ordinary[18], although the presence of a dust lane and of H II emission near its centre suggests that a recent burst of star formation occurred near its centre[5,7]. We estimate, taking an intergalactic extinction of $A \approx 0.43$ magnitudes (mag) (ref. 19) into account, that within the observed isophotal magnitude $B_{25} \approx 16''$ ($\sim$5.6 kpc)[19] and adopting $M/L_{\rm B} \propto L^{0.3}$ (ref. 20), NGC 1260 has a mass of $M(R = 5.6\,{\rm kpc}) \approx 3 \times 10^{10} M_\odot$, where R is the radius from the centre of NGC 1260. We assume that the mass enclosed within R is (as is the case for the Milky Way[21]) described with $M(R) = \mu R^{1.2}$. For NGC 1260 $\mu \approx 9.5 \times 10^5 M_\odot$, so we can then calculate the lower limit to the tidal radius[22] for a cluster of mass m in a circular orbit at distance R from the centre of NGC 1260.

Star clusters that experience core collapse before the most massive stars have left the main sequence can grow a supermassive star via collision runaway[8,23–25]. The mass which can then grow within $\lesssim$3 Myr can be estimated using equation (2) of ref. 17. Here we have to make some assumption about the stellar mass function in the cluster, but for clarity, to adopt a mean mass of $\langle m \rangle = 0.5M_\odot$ is sufficient without detailed knowledge of the exact shape of the initial mass function. For a reasonable range of cluster densities and distances from the centre of NGC 1260 we can now calculate the mass that can be grown in the cluster in $\lesssim$3 Myr.

In Fig. 1 we present the results of our calculations using a King[26] model with the depth of the central potential expressed by the dimensionless parameter $W_0 = 8$, which can produce at most a $\sim 920M_\odot$ star in a collision runaway. For shallower as well as for more concentrated King models the maximum mass for the supermassive star decreases, as well as the mass of the cluster that produces such stars.

The last collision before the supernova must have occurred with a relatively unevolved main-sequence star, and deposited large quantities of hydrogen on the surface of the collision product. By the time of the supernova not all the surface hydrogen of the last collision was blown away, given that about $1M_\odot$ of hydrogen was observed in the supernova[5]. The remainder of the hydrogen deposited on the stellar surface during the last collision was found in the interstellar medium surrounding the supernova, and exceeds some 0.5–$5M_\odot$ (refs 5, 7) but could be as high as 20–$30M_\odot$ (ref. 5). This mass may have come from the strong stellar wind in the last few 10^4 years before the supernova, blowing away the hydrogen which was deposited to the stellar surface during the collision. A tentative upper limit for the rate of mass loss of the progenitor star is $\dot{m} = 5 \times 10^{-4} M_\odot\,{\rm yr}^{-1}$ to $1.4 \times 10^{-4} M_\odot\,{\rm yr}^{-1}$ (ref. 5). These observed mass-loss rates are consistent with those of detailed evolutionary calculations for stars of 500–$1{,}001M_\odot$ (refs 27, 28). At this mass-loss rate it takes roughly 4×10^4 to 1.4×10^5 years to blow $20M_\odot$ in the form of a stellar wind from the surface of the supermassive star. This timescale is of the same order as our estimated average time between collisions of $\lesssim 7.3 \times 10^4$ years (see Fig. 1).

The luminosity of the supernova explosion in collapsar models is driven by the angular momentum transfer from the critically rotating black hole to its surrounding torus. The available energy reservoir, and thus the supernova brightness, would then be proportional to the

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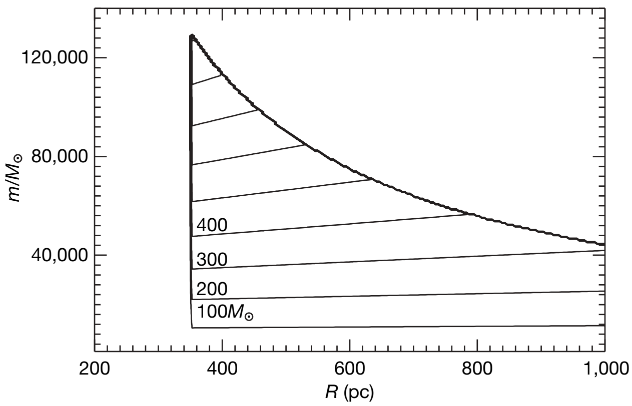

Figure 1 | Mass of the collision runaway star as a function of cluster mass and its distance to the centre of NGC 1260. The contours, computed for a King model with $W_0 = 8$, give the mass of the runaway collision star as a function of the distance to the centre of the galaxy NGC 1260 and the mass of the star cluster. The lowest four contours are labelled by the mass of the supermassive star (in solar masses) with constant increments of $100M_\odot$ for subsequent curves. A star cluster less massive than about $6{,}000M_\odot$ is unable to experience core collapse and produce a collision runaway before it dissolves in the tidal field of the parent galaxy, whereas star clusters in the top right corner are unable to reach core collapse before the most massive stars experience a supernova. The most massive object that can form is $\sim 920M_\odot$ in a $m = 1.3 \times 10^5 M_\odot$ cluster. An $m = 48{,}000M_\odot$ cluster with $W_0 = 5$ can produce at most a $340M_\odot$ supermassive star, whereas a King model with $W_0 = 11$ can produce a star of at most $480M_\odot$ in a cluster of $68{,}000M_\odot$. With an average mass increase per collision of $\sim 20M_\odot$ (refs 8, 23), the supermassive star then has experienced at most some 40 collisions between the moment of gravothermal collapse of the cluster core and the moment that the supermassive star explodes in a supernova. The mean time between collisions for this model is then $\lesssim 7.3 \times 10^4$ years. For shallower as well as for more concentrated models the time between collisions is larger; $\lesssim 1.7 \times 10^5$ years for $W_0 = 5$ and $\lesssim 1.2 \times 10^5$ years for $W_0 = 11$. For a wide range of reasonable cluster parameters it appears likely that a collision runaway ensues and produces a supermassive star.

mass of the black hole[29]. The observed brightness of SN 2006gy would then be consistent with the collapse of an unusually massive star, and the consequent formation of a rather massive ($\gtrsim 100M_\odot$) black hole. We are unaware of detailed simulations of such an unusual supernova to bolster our arguments, but the consequences for the supernova seem to be profound and we encourage further research in this direction.

The amount of hydrogen in the pre-supernova stellar envelope, the amount of hydrogen in the surrounding interstellar medium, the mass-loss rate of the supernova progenitor derived from the observations and the enormous brightness of the supernova all fall within a reasonable uncertainty of the values we derive here on the basis of the collision runaway scenario. We therefore conclude that a collision of a $\sim 20M_\odot$ main-sequence star with a supermassive star $\sim 10^5$ years before the supernova could conveniently explain the range of oddities surrounding SN2006gy. We predict that a young ($\lesssim 5$ Myr), dense and massive ($10^4 \lesssim m \lesssim 10^5 M_\odot$) star cluster is present at the location of the supernova. At the moment the star cluster cannot be seen, but adopting a mass-to-light ratio of ~ 0.6, which is consistent with the Starburst99 (ref. 30) models for a $\lesssim$5-Myr-old stellar population, the cluster should become noticeable as soon as the supernova fades below an absolute magnitude of about -8.2 mag for a $10^5 M_\odot$ star cluster, and -5.7 mag for a $10^4 M_\odot$ star cluster.

The environment in which the collision runaway can be initiated is rather exotic, as the cluster has to be sufficiently massive and dense to warrant dynamical core collapse within a few million years. In star clusters sufficiently massive to grow a massive collision product there are typically between 60 and 600 stars $>8M_\odot$, and consequently only one out of 60–600 type Ib/c or type II supernovae in these clusters will be of this peculiar bright type, as SN2006gy is. If in a nuclear or a normal starburst ten per cent of all stars are formed in sufficiently dense clusters, one would expect about one out of 600–6,000 supernovae to be of this type.

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