The brightest supernova ever recorded, powered by the death of an extremely massive star

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Supernovae resulting from the deaths of massive stars span a wide range of peak luminosities, usually reached within 30 days after explosion. Their diversity depends on the star's initial mass and rate of mass loss during its lifetime. Stars born with initial masses above 40 times the mass of the Sun are expected to shed their hydrogen envelopes to expose their He core before they die, resulting in supernovae with little or no evidence for hydrogen gas observed in their spectrum. Here we report on our discovery and follow-up observations of SN 2006gy, which reveal that it reached a peak luminosity at least 3 times greater than any other supernova seen to date, and far greater than most others. We find that a large ejected mass of order 100 Solar masses is required to power its enormous total radiated luminosity, indicating a total kinetic energy of more than 10^{52} ergs. This suggests that SN 2006gy marked the demise of an extremely massive star that, contrary to expectations, failed to shed its massive hydrogen envelope. A circumstellar shell that surrounded the progenitor star has a large mass and expansion speed, effectively ruling-out certain types of progenitor stars. Based on a number of lines of evidence, we suggest that the progenitor was a very massive evolved object like eta Carinae, which is the most luminous star known in the Milky Way. These observations suggest that the most massive stars can explode earlier than expected, and can create bright supernovae instead of dying ignominious deaths through direct collapse to a black hole. If such a fate is common, then supernovae from the first stars in the universe, which may have been extremely massive, will be more numerous than previously believed.

We discovered SN 2006gy on 18.3 September 2006 [1], but the transient was interpreted by others as a bright active galactic nucleus (AGN) rather than a supernova [2]. However, in the subsequent two months, our group continued to follow SN 2006gy, and with additional astrometric, photometric, and spectroscopic data we announced that it did indeed appear to be a supernova after all, and not an AGN [3]. Figure 1 is a high-resolution image of the host galaxy, which clearly indicates that SN 2006gy is separated from the nucleus of its parent galaxy by about 1 second of arc (or only about 350 pc at the galaxy's distance of 73 Mpc), confirming that it is not an AGN.

SN 2006gy has quickly distinguished itself as unique from other supernovae in two important ways. First, after correcting for distance and extinction it is the most luminous supernova ever seen, and second, it has exhibited a remarkably slow rise to its peak luminosity. Figure 2 shows the visual-wavelength light curve of SN 2006gy obtained by our group, compared to a sample of several other representative supernova light curves. SN 2006gy has recently peaked and is now on the decline, allowing a preliminary interpretation of the cause for its peculiar behavior. In the discussion below, we examine several lines of evidence suggesting that SN 2006gy may have been the death of a very massive star with much of its hydrogen envelope still intact, and surrounded by a massive circumstellar nebula. In many respects, the type of progenitor we infer for SN 2006gy resembles the luminous blue variable (LBV) star eta Carinae in our own Galaxy, as discussed below.

SN2006gy was classified as a type IIn supernova exhibiting narrow lines of hydrogen in its spectrum at early times [4], although the spectrum has notable differences compared with prototypes of this class. It dramatically violates the expectation that type II supernovae are generally fainter than type I supernovae (Figure 2 includes a typical type II supernova SN1999em [5]), and that type IIn supernovae typically show a more rapid rise, taking only about 20 days to reach their peak visual brightness [6]. SN2006gy, by contrast, took about 70 days to climb to its peak. Also, for at least100 days it remained brighter than –20.5 mag, which is still more luminous than any other supernova. Interestingly, SN1987A took a similarly long time to reach its peak luminosity [7], but it was 250 times fainter than SN2006gy.

Simply put, for a supernova to be extremely luminous and to remain so for such an extended time is truly spectacular, and requires a vast reservoir of thermal energy to continually power the observed radiation. Integrating over the light curve in Figure 2 and adopting no bolometric correction, we calculate a total radiated energy of $E_{rad} = 7\times10^{50}$ ergs, where the uncertainty is dominated by the adopted extinction of the host galaxy (see Fig. 2). This is a phenomenal amount of radiated energy, about 100 times more than that of most type II supernovae. It ultimately comes from the release of thermal energy contained in the envelope of the star that was ejected. Radioactive decay is not expected to power the light curve until late times*, and the luminosity from interaction with circumstellar material probably makes a relatively small contribution, as we discuss later. The initial gravitational binding energy of the star should equal the initial thermal energy in the envelope, and the energy deposited by the shock to unbind the star may have contributed as much as half the radiated energy. Therefore, we divide E_{rad} by a factor of 2 to estimate the contribution from that initial thermal energy contained in the star's envelope. This can provide an estimate of the ejected mass from

$$\frac{E_{rad}}{2} \approx \frac{GM_* M_{ej}}{R_*},$$

where M_*, M_{ej}, and R_* are the stellar mass, ejected mass, and stellar radius at the time of explosion, respectively. The ejected radiating mass can then be expressed as

$$M_{ej} \approx 115\ M_\odot \times (E_{rad}/10^{51}\ \text{ergs})^{1/2}\ (R_*/100\ R_\odot)^{1/2}\ (f)^{-1/2}\ ;\ (f < 1),$$

where f is the fraction of the total mass ejected in the explosion. We have adopted $R_*=100\ R_\odot$ (7×10^{12} cm), appropriate for a blue supergiant with a luminosity $L=4\times10^6\ L_\odot$ (1.6×10^{40} ergs/s) and an effective surface temperature T_{eff}=20,000 K, similar to eta Carinae's present state [8]. This is the smallest plausible radius for a blue supergiant with a massive hydrogen envelope. Thus, from our measured value of E_{rad}, we find a likely ejected mass of $\sim100\ M_\odot$, if we adopt a hypothetical value $f\approx0.9$. The total mass of the progenitor at the time of explosion would then have been $\sim110\ M_\odot$. The uncertainty

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* One potential caveat would be if SN2006gy was a special type of supernova that may occur in very massive stars in the early universe, where the star's Fe/Ni core can be disintegrated by pair-production instability, so that a large mass of ejected Ni could power the luminosity with radioactive decay. However, even if it is possible, this interpretation would not alter our essential thesis that the SN2006gy was the explosion of a very massive star.

in this mass could be as high as a factor of 2, but is difficult to quantify because it depends on our assumptions and the future behavior of the light curve, rather than measurement error. However, our assumptions were made so as to make the mass estimate conservative. For example, to estimate E_{rad}, we only included the observed radiation thus far; while SN2006gy is in decline, it remains more luminous than any other supernova at –21 mag, so the total radiated energy will certainly be higher. Also, the extinction we adopted may be low. In any case, even allowing for factors of 2, the huge amount of radiated energy requires that the progenitor of SN2006gy was a very massive star at the time it exploded. It is likely that its initial mass at birth was near the putative upper limit to stellar masses of ~150 $M_{\odot}$ [9].

Expansion velocities seen in spectra of the supernova also provide critical clues to its nature. The spectrum of the broad Hα line in Figure 3 indicates an expansion speed of about 4,000 km/s. If we adopt the ejecta mass of ~100 $M_{\odot}$, we find a total kinetic energy of roughly 1.6×10^{52} ergs. This large energy is consistent with the idea that SN2006gy was caused by the death of a very massive star.

Based on the lack of significant deceleration since early times, as well as the limit that the observed X-ray emission from SN2006gy sets for the progenitor star's mass-loss rate (see Supplementary Information), we conclude that interaction with circumstellar material is unlikely to dominate the radiated luminosity from SN2006gy during its first ~100 days. This is critical for interpretations that rely on the conversion of kinetic energy to power the observed radiation, as in a scenario where a type Ia SN explodes within a dense asymptotic giant branch (AGB) star's wind (sometimes called a type IIa supernova). Recently, Ofek et al. [10] have advocated this interpretation for SN2006gy, as for the very bright SNe 2002ic and 2005gj in Figure 2 [11,12]. However, the efficiency of converting kinetic energy to radiation results in a catch 22. Namely, a very large mass of ejecta and a very large kinetic energy of order 10^{52} ergs would be required to contribute significantly to the light curve. While this would be consistent with the ejecta mass and energy we derive here (motivating our claim of a factor of ~2 uncertainty in the derived mass), the "type IIa" model requires nearly 100% efficiency for converting ~10^{51} ergs of input kinetic energy to power the observed luminosity, where ~1 $M_{\odot}$ of ejecta sweeps up ~1 $M_{\odot}$ of material. This is unlikely, given that the SN 2006gy expansion speed has not decelerated much. Thus, we conclude that the radiative energy budget is a severe obstacle to the "type IIa" interpretation for SN 2006gy.

The high-resolution spectrum in Figure 3 contains a narrow component to the Hα line, which exhibits a clear P Cygni absorption profile. The supernova is therefore expanding into a hydrogen-rich stellar wind or circumstellar nebula of the progenitor star, which has an expansion speed of 130-260 km/s. This expansion speed in the progenitor's environment is much faster than typical wind speeds of AGB stars (10-20 km/s), effectively ruling out the interpretation of SN2006gy as a type IIa supernova noted earlier [10]. This speed is also too fast for a red supergiant wind (20 - 40 km/s), and an order of magnitude too slow for the wind of an O supergiant or Wolf-Rayet (WR) star progenitor. However, this speed is consistent with an LBV wind or nebula [8]. The fastest LBV nebula known is the one around eta Carinae, with a maximum speed of about 650 km/s, but it would show a deep absorption trough at -150 to -250 km/s were it viewed from intermediate latitudes [13].

At a distance of 73 Mpc, the luminosity of the narrow component of the Hα line in the bottom panel of Figure 3 would be about $L_{H\alpha}\approx4.4\times10^{5}$ $L_{\odot}$. Using this Hα luminosity, and assuming that the line originates from a circumstellar shell nebula of constant density, the nebular ionized gas mass can be expressed as

$$M_{H\alpha} \approx \frac{m_H L_{H\alpha}}{h\nu \alpha^{eff}_{H\alpha} n_e}$$

where $h\nu$ is for an Hα photon, $\alpha^{eff}_{H\alpha}$=8.64×10^{-14} cm^3 s^{-1} is the case B Hα recombination coefficient, and n_e is the average electron density. This yields $M_{H\alpha}$≈11.4 $M_\odot$ ($L_{H\alpha}/n_e$). We do not know the electron density in the nebula around SN 2006gy, but values of 10^5-10^6 cm^{-3} are the highest densities typically seen in young LBV nebulae like the one around eta Carinae [13,14]. With the observed Hα luminosity and densities of this order, it is difficult to avoid a nebular mass below 2 $M_\odot$, and it could easily be as high as 20-30 $M_\odot$. Interestingly, such large numbers would be consistent with the ≥12.5 $M_\odot$ nebula around eta Carinae [16]. Lower densities typically seen in circumstellar nebulae around lower-mass stars would require implausibly high emitting masses to account for the observed radiation, exceeding their own stellar masses. Thus, the flux of the narrow Hα component that we observe is only likely to arise in the circumstellar nebula of an extremely massive star.

We suspect that the very slow rise time in the visual light curve of SN2006gy may be due to a combination of its relatively slow expansion speed and a small radius at the time of explosion. SN1987A also took a long time to reach its peak luminosity [7], which is generally attributed to its explosion as a compact blue supergiant instead of as a large red supergiant [15]. A small radius at the time of explosion would be consistent with the hypothesis that SN2006gy had a very massive progenitor star, because stars with initial masses above roughly 40 $M_\odot$ never develop sufficiently cool photospheres to become red supergiants. Instead, they are prevented from getting to that point by a very unstable stage of evolution when they are seen as LBVs [8]. During this brief evolutionary phase, a massive star might undergo bursts of mass loss when it can shed more than 10 $M_\odot$ of material in a decade [16]. These events are seen in other galaxies as faint type IIn supernovae, or “supernova impostors” [17]. They may dominate the mass loss of the most massive stars, shedding more total mass than line-driven winds during the star’s lifetime [18]. Consequently, LBV stars are frequently surrounded by circumstellar nebulae with masses of order 10 $M_\odot$ [18], like the one we infer to exist around SN2006gy based on the narrow component of the Hα line.

Thus, while detailed modeling of the light curve, spectrum, and continued observations should definitely be undertaken to improve our estimates of the ejected mass and energy, it appears that all available observations are broadly consistent with the hypothesis that the progenitor of SN2006gy was a very massive star that retained a massive hydrogen envelope at the time it exploded. If this hypothesis of explosion as a massive LBV is correct, it would have important consequences for our understanding of stellar evolution. It is currently thought that the instability in the LBV phase is responsible for the mass shedding that marks the transition from the end of H burning to core He buring, after which a star appears as a He-rich WR star [18,19,20]. The core He burning WR phase that follows after the massive hydrogen envelope is stripped away is expected to last a few hundred thousand years before the star reaches even more advanced stages of nuclear burning and finally explodes [20]. If LBVs explode before reaching the WR phase, though, it means that they could be in much more advanced stages of nuclear burning than currently predicted by stellar evolution theory. SN2006gy is not our first hint that LBVs may explode early [21,22,23], but as the brightest supernova ever recorded, it is perhaps the most extreme case of a massive star's death.

If the most massive stars can indeed explode before the WR phase, then our current ignorance of the instability underlying the LBV evolutionary phase presents a critical challenge for stellar evolution. Namely, SN2006gy may be giving us a clue that the wild instability of the most luminous LBVs like eta Carinae may be an early warning sign of a massive star's imminent demise. One implication is that we had better keep a watchful eye on eta Carinae.

Acknowledgments

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Supplementary Information

Why interaction with circumstellar material does not power the radiated luminosity of SN2006gy

The expansion speed of 4000 km/s that we observe near peak brightness is critical for addressing the extent to which interaction with circumstellar material may power the observed radiation, because it has not changed much from the initial expansion speed of ~4500 km/s seen in the broad P Cygni absorption of Hβ at only a few days after discovery [4]. If the expanding blast wave has only slowed by about 10% in the first few months, conservation of momentum dictates that the mass of swept up material is only about 10% of the ejected mass. This makes it difficult to extract E_{rad}=7×10^{50} ergs from a type Ia SN that has a kinetic energy of ~10^{51} ergs.

Furthermore, the conditions required to explain SN 2006gy as a "type IIa" supernova are unprecedented. Ofek et al. [10] find that the supernova must expand into the wind of an asymptotic giant branch (AGB) star that has had a mass-loss rate of 0.01 $M_{\odot}$/yr for the past 100 yr. Such powerful winds are not observed in even the most extreme AGB stars, and this enhanced mass-loss episode from the companion would need to be synchronized with the supernova.

Furthermore, recent observations by the Chandra X-ray Observatory have resolved SN 2006gy in the soft (0.5-0.8 keV) X-ray band, revealing an X-ray luminosity of about 1.65×10^{39} erg/s. This constrains the mass-loss rate of the progenitor star to be less than 10^{-4} $M_\odot$/yr, as explained in more detail below. This effectively rules out the interpretation of SN2006gy as a Type Ia SN exploding in a dense AGB environment, because that model requires a mass-loss rate 100 times higher than what is permitted by the observed X-ray flux. It seems far more straightforward to invoke the explosion of a very massive star like eta Carinae.

Using the Chandra X-ray Observatory, we observed SN2006gy at t=57 days after discovery. At the position of SN2006gy, four counts were detected in an exposure of 29.743 ks with the Advanced CCD Imaging Spectrometer after correcting for the background flux, which precludes a detailed spectral analysis. However, the counts were all detected below 1.5 keV, giving some indication of the spectral shape. We assume a thermal plasma spectrum (Raymond-Smith) with kT = 1 keV to estimate the luminosity. Such thermal spectra have successfully fit the X-ray spectra of supernovae, and temperatures much higher than this would result in significant emission detectable by Chandra (which was not seen). Based on the observed reddening toward 2006gy of E(B-V)=0.74 mag [10], we assume an X-ray absorbing column of $n_H=4.1\times10^{21}$ cm^{-2}. From this absorbed thermal spectral model, we calculate an intrinsic X-ray luminosity (integrated over photon energies of 0.5 to 2 keV) of 1.65×10^{39} erg/s for SN 2006gy.

We expect this X-ray emission to have arisen from the interaction of the outgoing shock with the circumstellar material. This interaction has been explored in detail [29]. We interpret the softness of the X-ray emission as having a reverse-shock origin, and we use the adiabatic case [29,30], giving

$$L_{rev} = 2.0\times10^{35}\ \zeta\ (n-3)(n-4)^2\ (T_8)^{-0.24}\ \exp\{-0.116/T_8\}\ (Mdot_6 / v_w)^2\ (V_4)^{-1}\ (t/10d)^{-1} \text{ ergs/s/keV},$$

where L_{rev} is the reverse shock luminosity of 1.65×10^{39} erg/s, ζ=0.86 for solar abundances, n is the index of the ejecta density profile $\rho_{SN} \propto t^{-3} (r/t)^{-n}$, which we take to be n=7, T_8 is the temperature in units of 10^8 K, which for 1 keV is 0.116, $Mdot_6$ is the progenitor star's stellar wind mass-loss rate in units of 10^{-6} $M_\odot$/ yr, v_{w1} is the wind velocity in units of 10 km/s, V_4 is the shock velocity in units of 10^4 km/s, t is the time since explosion, which is 57 days for the Chandra observation. We assume that the main shock is expanding at the observed speed of 4500 km/s, so that V_4=0.45, and it is running into a pre-existing medium for the progenitor's wind expanding at ~200 km/s (v_w=20) indicated by the narrow P Cygni absorption component in Figure 3. With the observed soft X-ray luminosity, this implies a mass-loss rate for the progenitor star of 6.7×10^{-5} $M_\odot$/yr. This is higher than a typical AGB star's wind, but much lower than the 0.01 $M_\odot$/yr required to account for the observed luminosity of SN2006gy. Interestingly, however, this mass-loss rate that we derive approaches the observed mass-loss rate of eta Carinae, which is about 10^{-3} $M_\odot$/yr [8].

FIGURE 1

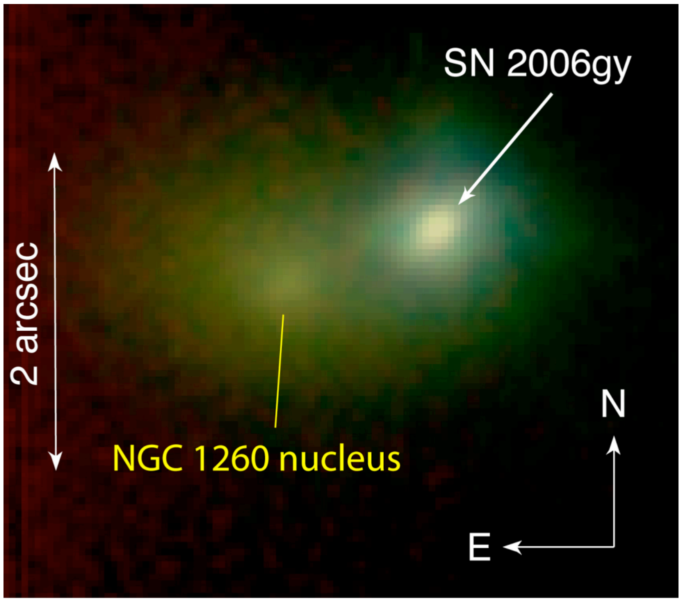

Fig. 1 – High-resolution false-colour infrared image of SN 2006gy and the nucleus of NGC 1260 showing a clear offset of the supernova from the galaxy center. Images at three wavebands (J central wavelength 1.2 micron; H central wavelength 1.6 micron; Ks central wavelength 2.2 micron) were obtained on 4 November 2006 UTC using the Adaptive Optics (AO) system in Laser Guide Star (LGS) mode [24] on the Shane 3-meter Telescope at Lick Observatory, Mt. Hamilton, California. The total integration time in each band was 480 sec, accumulated over 8 exposures. The native pixel scale of the 256×256 Rockwell PICNIC array is 0.076 arcsecond $pixel^{-1}$; our custom reduction pipeline, which accounts for the sub-pixel dithering between exposures in a given bandpass, produces final mosaiced images with a pixel scale of 0.04 arcsec $pixel^{-1}$. The SN itself was bright enough to use as a "tip-tilt" star for the LGS system and produced an effective resolution full-width half-maximum of 200 mas at H-band. The measured offset of the SN from the centroid of the galactic nucleus is 941 milliarcsec (mas) West, 363 mas North, with a 1-σ uncertainty of 10 mas in each direction; this confirms and improves the earlier offset measurement using the KAIT imaging data of 880 mas West, 140 mas (uncertainty of 80 mas) [3]. On 5 Nov 2006 UTC, we also used the AO-LGS system in polarimetry mode but found no evidence that the infrared continuum of the SN was polarised above the 3% level. Note that NGC1260 is an S0/Sa galaxy, so it may have active star formation. We see extended Hα emission along the slit in some of our spectra (not shown), it is detected by IRAS, and high resolution images may show a considerable dust lane [10]. Additionally, SN2006gy is only ~350 from the galaxy's nucleus.

FIGURE 2

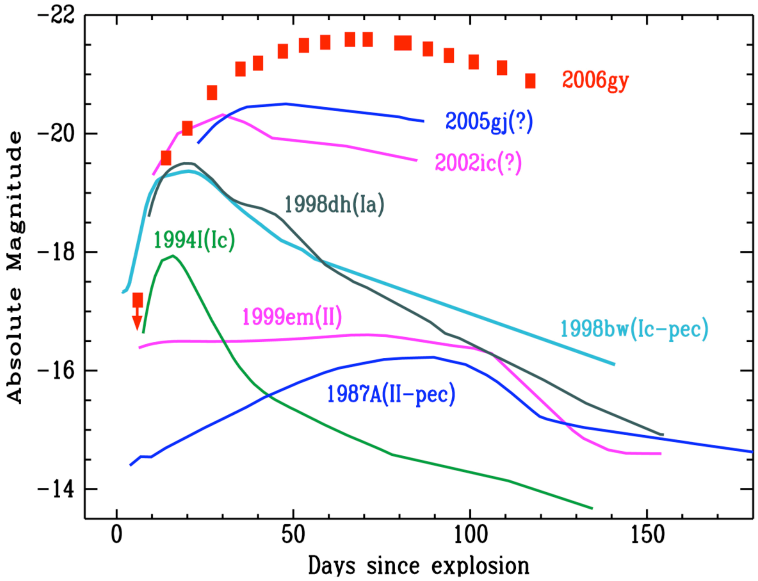

Fig. 2 – Comparison of the light curve of SN 2006gy to other SNe. The unfiltered KAIT images for SN 2006gy were used to derive a R-band light curve for SN 2006gy. Each image is aligned to a deep pre-SN image, and the contamination of the host galaxy emission is carefully removed by scaling the images to the same level. The net flux for the SN is then compared to 19 bright stars using calibrations from the USNO B1 catalog. To put the flux of SN 2006gy on an absolute magnitude scale, we adopt a distance of 73.1 Mpc (using H_0 = 72 km s^{-1} Mpc^{-1} and a recession velocity of 5361 km/s) for the host galaxy NGC 1260. We also adopted a Galactic reddening of A_R = 0.43 mag [25] and a host-galaxy reddening of A_R =1.0 mag. Strong Na I D absorption lines are seen in the spectrum of SN 2006gy which are suggestive of a large host-galaxy extinction; it could be as high as A_R =2.5 mag, beyond which the continuum shape in the spectrum would be too blue for the Rayleigh-Jeans tail of a supernova photosphere. Thus, our estimate of E_{rad} in the text and the mass we derive from it are conservative estimates. For instance, Ofek et al. [10] adopt a larger extinction and find a peak that was ~0.5 mag brighter. We also plot the light curves for several other SNe in the R-band whenever possible. SN 1998dh is a typical Ia. The data were from our unpublished photometry database, and a typical absolute magnitude of M_R = -19.5 mag is assumed. SN 1999em is a typical type II and the photometry data were adopted from Leonard et al. [5]. SN 1994I is a typical Ic and the photometry was adopted from Richmond et al. [26]. SN 1987A is a peculiar type II, with a broad light curve but a low luminosity. The photometry is from Hamuy et al. [7] and we adopt a distance modulus of 18.50 mag to its host galaxy, the LMC. The light curve for SN 1998bw is adopted from Galama et al. [27]. We also plot two similar SNe to SN 2006gy. The data for SN 2002ic is from Hamuy et al. [12], and the data for SN 2005gj is from Aldering et al. [13]. Both SN 2002ic and SN 2005gj were interpreted in the context of a type Ia exploding in a massive circumstellar envelope by some groups [12,13]. Benetti et al. [28], however, suggested that SN 2002ic was the collapse of a stripped-envelope, massive star in a dense medium.

FIGURE 3

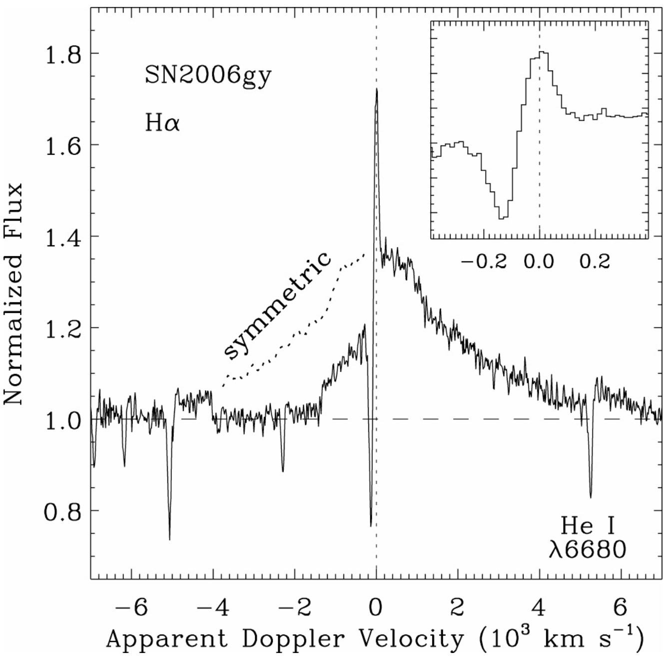

Fig. 3 – The spectrum of the Hα line seen in SN2006gy, with the flux normalized to the underlying continuum level. The spectrum was obtained on 2006 November 24.51 UT using the DEIMOS spectrograph on the Keck II telescope. Using a customized version of the DEEP data reduction pipeline, we obtained sky-subtracted, rectified 2-D images, and wavelengths were calibrated with respect to an internal arc lamp. We corrected for telluric absorption with comparison to the standard BD+284211. The inset zooms-in on the narrow P Cyg line profile that we believe to be associated with slower circumstellar ejecta. Velocities are measured relative to this narrow emission component.

The broad component of the line is narrower (FWHM≈2300 km/s) than most type II supernovae [5], and the profile is clearly asymmetric. The dashed line labeled "symmetric" is the red side of the broad Hα line reflected to blueshifted velocities. It is clear that there is significant blueshifted Hα absorption from 0 km/s out to a sharp blue edge at about –4000 km/s. At that point, the blueshifted emission recovers to the level expected for a symmetric profile and gradually declines to the continuum level at about –6000 km/s, just as on the red side of the line (which overlaps with He I λ6680). The expansion speed of about 4000 km/s is similar to the velocity observed at early times [4] (the line wings extending out to ±6000 may be due to electron scattering). However, it is less than half the speed of normal type II supernovae of 10,000 km/s [5]. For the same explosion energy as imparted in a typical supernova, this would imply an ejected mass that is at least 4 times larger, or at least 40 $M_{\odot}$. This would imply that a heavy stellar envelope mass-loaded and slowed the supernova shock. A larger total energy than a normal supernova would allow even larger masses, however (see text). The blueshifted absorption trough of the narrow component in the bottom panel has a minimum at about –130 km/s relative to the peak of the narrow emission, and reaches speeds of –260 km/s at its blue edge. Similar absorption features were seen in lines of He I, Si II, Fe II, Ca II, O I, etc.