Supernova SN2006gy as a first ever Quark Nova?

Denis Leahy and Rachid Ouyed

Department of Physics and Astronomy, University of Calgary, 2500 University Drive NW, Calgary, Alberta, T2N 1N4 Canada

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Abstract. The most luminous Supernova SN2006gy (more than 100 times brighter than a typical supernova) has been a challenge to explain by standard models. For example, pair instability supernovae which are luminous enough seem to have too slow a rise, and core collapse supernovae do not seem to be luminous enough. We present an alternative scenario involving a quark-nova (an explosive transition of the newly born neutron star to a quark star) in which a second explosion (delayed) occurs inside the ejecta of a normal supernova. The reheated supernova ejecta can radiate at higher levels for longer periods of time primarily due to reduced adiabatic expansion losses, unlike the standard supernova case. We find an encouraging match between the resulting lightcurve and that observed in the case of SN2006gy suggesting that we might have at hand the first ever signature of a quark-nova. Successful application of our model to SN2005gj and SN2005ap is also presented.

Key words. stars: evolution — stars: neutron — supernovae: individual (SN2006gy) – dense matter

1. Introduction

Supernova (SN) SN2006gy is the most luminous supernova yet observed (more than 100 times brighter and significantly longer-lasting than a typical supernova); it has so far challenged existing models. The fundamental question is how to power the observed lightcurve for so long (Smith et al. 2007; Ofek et al. 2007). Smith et al. (2007) rule out circumstellar medium (CSM) interaction based on the low observed X-ray flux and other properties compared to known CSM powered SNe. On the other hand, Ofek et al. (2007) argue that X-rays would be absorbed in the CSM so that the lack of X-rays does not rule out the CSM interaction mechanism. Smith et al. (2007) instead favor pair instability supernova (PISN) model by energy argument; 22 $M_\odot$ of $^{56}$Ni is needed to account for the peak luminosity. Scannapieco et al. (2005) considers PISNs for masses between 150$M_\odot$ and 250$M_\odot$. PISN models brighter than $M_{AB} \sim -21$ occur only for the most massive stars. Langer et al. (2007) explore the metallicity range for PISN and conclude they can occur in the local universe. Despite the fact that PISN models of Scannapieco rose too slowly compared to SN2006gy no better alternative was available to Smith et al. (2007).

Nomoto et al. (2007) further consider PISN of 166 $M_\odot$, ejected mass and 15 $M_\odot$ ejected $^{56}$Ni. They clearly demonstrate that the lightcurve has too slow of a rise to be consistent with SN2006gy. They can artificially fit the early parts ($\leq 120$ days) of the SN2006gy lightcurve by a PISN model with reduced ejected mass of about 50 $M_\odot$ (including the 15 $M_\odot$ of $^{56}$Ni), but point out that such a low ejected mass is inconsistent with the 15 $M_\odot$ $^{56}$Ni mass. Umeda & Nomoto (2007) as an alternative to PISN reconsider nucleosynthesis in core-collapse explosions (initial mass less 100 $M_\odot$). Their main findings are that the $^{56}$Ni mass depend on initial stellar mass (which determines progenitor C+O core mass) and explosion energy (which determines core mass fraction converted to $^{56}$Ni). The maximum $^{56}$Ni mass (of $\sim 13M_\odot$) was obtained for the most massive star with $M_{CO} \sim 43M_\odot$ and explosion energy of $\sim 2 \times 10^{53}$ ergs which they note to be unrealistically large.

Two recent papers make use of the idea of shock energy being deposited in an extended envelope to minimize adiabatic losses so that the light curve of SN2006gy can be powered by shock energy. Woosley, Blinnikov, & Heger (2007) consider a pulsational pair-instability supernova, which leads to a second ejection. The interaction between the second and the first ejection powers the light curve, in contrast to a normal PISN which is powered mainly by a large $^{56}$Ni mass as discussed above. This gives rise to a light curve bearing some similarities to SN2006gy. Smith&McCray (2007) give a general argument that the light curve can be produced by shock propagating in an envelope with an initial radius of order of 60 AU, which avoids adiabatic expansion losses.

It has long been thought that the center of neutron stars may be dense enough that nuclear boundaries dissolve and a phase transition to matter made of up and down quarks occurs (Itoh 1970; Bodmer 1971). It was then conjectured by Witten (1984) that the addition of the strange quark to the mixture would lead to a true ground state of strongly interacting matter at zero pressure making the existence of quark stars an intriguing possibility (Alcock et al. 1986). Neutron star cooling studies show no strong incompatibility with standard neutron star models (e.g. Page 2004). However quark stars are not ruled out either: mass-radius studies still allow quark star equations...
of state (e.g. Leahy 2004). The transition from neutron star to strange star associated with SNe has been suggested previously (e.g. Horvath & Benvenuto 1988; Drago et al. 2007 and references therein). In addition a two-bang scenario was proposed in the context of SN1987A to explain the delayed neutrinos, where the delay is due to the collapse of the neutron star into a black hole or strange star (De Rujula 1987).

We propose a model based on additional energy input into the supernova ejecta: (i) The explosion occurs inside an extended expanding envelope; (ii) The delayed explosion is due to conversion of neutron star (NS) to a quark star (QS). No one has used the conversion from NS to QS to explain extremely bright SNe, nor has anyone used the crucial idea of delayed explosion. Benvenuto & Horvath (1989) explored the idea of conversion energy release to power SN1987A, which is a regular SN. However, they do not calculate any lightcurves, do not consider explosive conversion, nor do they make use of the conversion delay. In our work here, the additional energy input into the supernova ejecta is a consequence of an explosive conversion of a neutron star to a quark star namely, a Quark-Nova (QN). The new ideas here are: (i) the explosive conversion in the QN; (ii) the resulting re-energization of the SN ejecta. The QN energy input is delayed from the original core collapse explosion, allowing for re-energization of the SN ejecta at larger radius. As we show in this paper this allows for more luminous and long-lasting explosion since much of the radiation is emitted rather than being lost to adiabatic expansion. We first discuss the SN process.

In the QN picture (Ouyed et al. 2002; Keränen & Ouyed 2003; Keränen et al. 2005) it was shown that detonation rather than deflagration occurs, so that the converted core contracts and separates from the un-converted crust of the neutron star. Specifically, the core of a neutron star, that undergoes the phase transition to the quark phase, shrinks in a spherically symmetric fashion to a stable, more compact quark matter configuration faster than the overlaying material (the neutron-rich hadronic envelope) can respond. The resulting quark star initial temperature is of the order of 10-20 MeV since the collapse is adiabatic rather than isothermal (Keränen, Ouyed, & Jaikumar 2005). The energy released during the QN explosion can be as high as \( E_{\text{QN}} \approx 10^{53} \text{ erg} \) and involves baryon to quark conversion energy and gravitational energy release due to contraction. Unlike a core collapse supernova, a large fraction of the energy of a QN after the collapse is released in photons. This is due to unique properties of quark matter in the superconducting color-flavor-locked (CFL) phase (Rajagopal & Wilczek 2001; for more recent studies on the feasibility of the CFL phase and its properties see Pagliara & Schaffner-Bielich 2007 and Alford et al. 2007). As shown in Vogt et al. (2004) and Ouyed et al. (2005), the CFL phase favors photon emissions to standard neutrino ones. The time delay between the SN and the QN is controlled mainly by spin-down and the increase in core density of the neutron star (Yasutake et al. 2005; Staff et al. 2006), and secondly by the weak conversion between quark flavors (e.g. Bombaci et al. 2004).

The QN ejecta (< 0.1\( M_\odot \)); see Keränen et al. 2005 and Jaikumar et al. 2007), which is the left-over crust of the parent neutron star, is initially in the shape of a shell and is imparted with energy from the QN explosion. One can show that it is expanding relativistically with Lorentz factor of a few (Ouyed et al. 2007). Inside the SN ejecta the QN ejecta rapidly sweeps up enough mass to become sub-relativistic. In simple terms this sets up a second blast wave propagating outward and reheating the SN ejecta. This second blast wave causes reheating of the ejecta at larger radii, thus adiabatic losses occur on much longer timescale than for the initial SN explosion. This is the key to the long duration and high brightness of the radiation from the second (QN) shock. Simply put, in the normal SN the shock radiation is lost to adiabatic expansion before it can diffuse out while for the delayed shock case much of the radiation diffuses out before adiabatic losses dominate.

This paper is presented as follows: Section 2 describes the SN phase. Section 3 describes the effects of the second explosion on the SN lightcurve with application to SN2006gy. Section 4 deals with SN2005gj before briefly concluding in Section 5.

2. The SN phase: The first shock

Let us assume that a SN has exploded and processed its ejecta by explosive burning. In our simplified model the energy from the shock is deposited instantly heating the ejecta to an initial temperature \( T_{\text{SN},0} \). This initial state is that of an expanding ejecta with a central region of \(^{56}\text{Ni}\). The ejecta is uniformly expanding in time (i.e. the velocity is linear with radius at any fixed time) with the outer radius of the ejecta given by \( R = R_0 + v_{\text{SN}} t \) where \( R_0 \) is the size of the progenitor star and \( v_{\text{SN}} \) is the speed of the shocked SN material.

Due to outward diffusion of photons the atmosphere is moving inward in mass coordinates, slowly at first but faster as the density decreases in time. The ejecta interior to the atmosphere we refer to as the core. We will assume that the thermal energy in the exposed mass in the atmosphere (as the cooling front creeps inward) is instantly radiated. The interplay between uniform expansion and radiation diffusion defines the evolution of the photosphere as

\[
R_{\text{phot}}(t) = R_0 + v_{\text{SN}} t - D(t),
\]

where \( D(t) \) is the diffusion length

\[
D(t)^2 = D_0^2 + \frac{c}{n_{\text{ejec}} \sigma_{\text{Th}}},
\]

where \( c \) is the speed of light, \( \sigma_{\text{Th}} \) is the Thompson cross-section, and \( n_{\text{ejec}} = N_{\text{ejec}} / V_{\text{ejec}} \) is the particle density in the ejecta. For an ejecta of mass \( M_{\text{ejec}} \) and mean molecular weight \( \mu \), the total number of particles is \( N_{\text{ejec}} = (M_{\text{ejec}} / \mu m_{\text{H}}) \) where \( V_{\text{ejec}} = (4\pi/3)(R_0 + v_{\text{SN}} t)^3 \) is the volume extended by the ejecta and \( m_{\text{H}} \) is the Hydrogen atomic mass. We define \( D_0 \) as the initial diffusion lengthscale by setting \( n_{\text{ejec},0} \sigma_{\text{Th}} D_0 \sim 1 \) where \( n_{\text{ejec},0} = N_{\text{ejec},0} / V_{\text{ejec},0} \) with the initial volume \( V_{\text{ejec},0} = (4\pi/3)R_0^3 \).

The corresponding luminosity is

\[
L_{\text{SN}}(t) = c_a \Delta T_{\text{core}} n_{\text{ejec}} 4\pi R_{\text{phot}}(t)^2 \frac{dD(t)}{dt},
\]
where the specific heat is $c_v \sim (3/2) k_B$ and $\Delta T_{\text{core}} \sim T_{\text{core}}$ since the atmosphere cools instantly (i.e. cooling time is much less than the diffusion timescale); $k_B$ is the Boltzmann constant. The rate of mass flux from the core to the photosphere is determined by the velocity $dD(t)/dt$.

Ignoring input from radioactive decay, adiabatic expansion of the core leads to

$$T_{\text{core}} = T_{\text{SN,0}} \frac{R_0^2}{(R_0 + v_{\text{SN}} t)^2},$$

which is used when computing the SN luminosity. The effect of radioactivity consists of heat added to the core from $^{56}\text{Ni}$ and $^{56}\text{Co}$ decay keeping the core temperature high for weeks to months even in the presence of adiabatic expansion losses. For standard SNe both type I (e.g. Sutherland&Wheeler 1984) and most type II (e.g. Sunzette et al. 1992) the late time lightcurve is dominated by radioactivity. However this does not seem to be the case for SN2006gy since the radioactivity lightcurve peaks much later than the observed peak (see Figure 9 in Nomoto 2007).

3. The Quark Nova phase: The second shock

The QN goes off at $t_{\text{QN}}$ after the SN explosion. The QN shock propagating at speed $v_{\text{QN}}$ reaches the outer edge of the SN ejecta (becomes visible to the observer) at distance $R_{\text{QN}}$ and time $t_{\text{QN}} + t_{\text{prop}}$, where $t_{\text{prop}} = R_{\text{QN}}/v_{\text{QN}}$ is the propagation time delay for the QN shock to reach the edge. That is, the ejecta is first fully reshocked at a radius $R_{\text{QN}} = R_0 + v_{\text{SN}}(t + R_{\text{QN}}/v_{\text{QN}})$ heating up the SN material to a new temperature $T_{\text{QN,0}}$. The evolution of the new photosphere is then

$$R_{\text{phot}}(t) \simeq R_{\text{QN}} + v_{\text{SN}} t - D_{\text{QN}}(t),$$

where $D_{\text{QN}}(t)$ is the diffusion length with parameters reset at $t_{\text{QN}} + R_{\text{QN}}/v_{\text{QN}}$. Again, ignoring input from radioactive decay in the core, adiabatic expansion gives

$$T_{\text{core}} = T_{\text{QN,0}} \frac{R_{\text{QN}}^2}{(R_{\text{QN}} + v_{\text{QN}} t)^2}. \quad (6)$$

In a normal SN, adiabatic expansion rapidly cools the ejecta to 3000K. Here the SN ejecta within the photosphere stays hot after the QN shock for a long time. A simple estimate using eq.(6) yields 70 years before cooling to 3000 K. For example, including Bremsstrahlung cooling, for the first 10 days the ejecta outside the photosphere cools rapidly. However, it represents only a tiny fraction of the mass of the shocked SN ejecta. The bulk of the shocked SN ejecta, which moves outside the photosphere after 10 days, expands to low density quickly enough that the cooling can be neglected (due to the $n^2$ dependence of cooling).

In the case where the QN impacts into a perfectly spherical SN ejecta, the calculated luminosity has a sharp rise when the QN shock reaches the outer edge of the SN ejecta. This is followed by fairly flat period before a smooth decline due to the photosphere moving inwards ($R_{\text{phot}}$ decreasing). An example is shown in Figure 3 by the dash and long-dash lines (for $R$- and $V$-band, respectively) compared to the data from SN2006gy (Smith et al. 2007). The model corresponds to a SN explosion at $t = 0$ with $M_{\text{eje.}} = 60 M_\odot$, $R_0 = 10 R_\odot$, $v_{\text{SN}} = 3400 \text{ km s}^{-1}$. The QN explosion occurs at $t_{\text{QN}} = 15$ days with velocity $v_{\text{QN}} = 6000 \text{ km s}^{-1}$. The above velocities were based on Smith et al. (2007) who find extended wings in $H_\alpha$ of $\pm 6000 \text{ km s}^{-1}$ (our choice of $v_{\text{QN}}$). In addition there is a blueshifted $H_\alpha$ absorption up to $\sim 4000 \text{ km s}^{-1}$, which could be a signature of the first shock on which we base our choice of $v_{\text{SN}}$. The total thermal energy deposited by the QN shock in the SN ejecta to reheat it to $T_{\text{QN,0}} \sim 0.4 \text{ MeV}$ is of the order $3 \times 10^{52} \text{ erg}$ which consistent with QN explosion energetics. The sharp rise in the model occurs at $(t_{\text{QN}} + t_{\text{prop}}) = (15 + 19.6) = 34.6 \text{ days}$. No attempt was made to fit this model to the data due to the sharp rise in the model and the importance of asphericity on the lightcurve (see below).
3.1. Effect of asphericity on the lightcurve

As noted above, the model curve has a sharp turn on in the case of a QN explosion into a spherically expanding SN ejecta. The SN is likely to be asymmetric primarily due to variation in expansion velocity $v_{SN}$. We account for this by extending our model to take into account a range of $v_{SN}$. The main result is varying radius ($R_{QN}$) and time when the QN shock reaches the outer edge of the SN ejecta. That is,

$$R_{QN}(v_{SN}) = \frac{R_0 + v_{SN} t_{prop}^Q}{1 - \frac{v_{SN}}{v_{QN}}}$$  (7)

leading to a time delay for different parts of the ejecta of $t_{prop}^Q(v_{SN}) = R_{QN}(v_{SN})/v_{QN}$. We note that $v_{QN} > v_{SN}$ in order for the second shock to occur. If the range of velocities in the SN ejecta extends to lower values, the delay is less between the QN and the initial rise in the lightcurve.

The resulting light curve is a superposition of light curves from different parts of the reshocked SN shell, with different rise times, different peaks, and different shapes. The corresponding light curve is shown in Figure 2 (solid and dash-dot lines for $R$- and $V$-band, respectively) and corresponds to an SN explosion at $t = 0$ with $M_{ej} = 60M_\odot$, $R_0 = 10R_\odot$, $t_{QN} = 15$ days, $v_{QN} = 6000$ km s$^{-1}$, and $T_{QN,0} = 0.4$ MeV. The lightcurve was computed by averaging over 13 equal solid angle segments of a sphere with different velocities linearly spaced between the minimum and maximum values: 2000 km s$^{-1} < v_{SN} < 4800$ km s$^{-1}$. The lightcurve first turns on when the slowest ejecta ($v_{SN,min} = 2000$ km s$^{-1}$) is fully reshocked at $t_{QN} + t_{prop}^Q(v_{SN,min}) = (15 + 7.5) = 22.5$ days. The Smith et al. (2007) data was plotted with the first data point (an upper limit) at $t = 22$ days in order to match our model with the overall rise. The spikes in the lightcurve (dashed line) are due to pieces of the SN ejecta being lit up by the QN shock at different times, which would be smoothed out if the distribution of velocities were continuous. The SN material at lower velocities experiences the QN shock earlier resulting in larger adiabatic losses and lower peak brightness. We note that the first shock (namely the SN proper) is too faint to be seen due to the large distance to SN2006gy. Even when we add $4M_\odot$ of $^{56}$Ni to the first SN (this is the maximum $^{56}$Ni produced for a $60M_\odot$ progenitor; Nomoto et al. 2007) we estimate a magnitude $M_R \simeq -18.5$ at 22 days which is only slightly above the upper limit for detection. This may indicate that the SN produced less $^{56}$Ni than the maximum expected.

3.2. The plateau beyond 200 days

We first note that the maximum $4M_\odot$ of $^{56}$Ni from the SN cannot power the late time plateau at $M_R \sim -19$. Nomoto et al. (2007) points out that for core collapse explosions most of the C+O core that is exposed to a radiative shock with $T > 5 \times 10^9$ K is converted to $^{56}$Ni. An interesting aspect of our model is that the second shock due to the QN is a hot radiative shock and can convert much of the C+O (and Silicon and Magnesium) in the SN ejecta to $^{56}$Ni. We estimate the initially ejected C+O mass for the $60M_\odot$ model to be $\sim 25M_\odot$ (see Table 2 in Umeda&Nomoto 2007). The first shock converts the C+O to successive layers of $^{56}$Ni, $^{28}$Si, and $^{16}$O/$^{24}$Mg (see Figure 5 of Umeda&Nomoto 2007). We suggest that the QN explosion might convert enough of the $^{28}$Si, and $^{16}$O/$^{24}$Mg to $^{56}$Ni to power the plateau. These are all zero neutron excess nuclei and as discussed by Umeda&Nomoto (2007) shock nucleosynthesis at high temperatures in zero neutron excess matter primarily produces nearly pure $^{56}$Ni. Finally, let us note that the QN explosion can provide very high explosion energies (up to $\sim 10^{53}$ ergs) which further favors nucleosynthesis of $^{56}$Ni.

The late-time lightcurve may be an important way to differentiate between models. Late-time observations of SN2006gy (Smith et al. 2008) show that the observed luminosity at 400 days is consistent with $\sim 2.5M_\odot$ of $^{56}$Ni, which is too low to be consistent with the $^{56}$Ni mass required to power the peak ($\sim 20M_\odot$). In effect the late-time light curve rules out $^{56}$Ni higher than $2.5M_\odot$. Calculations of the total mass of $^{56}$Ni in our model are very sensitive to the density in the ejecta, and cannot be reliably estimated with our simplified model. This is left as future work.

The late-time lightcurve could alternately be re-emission of the SN peak light curve light by dust. We favor this idea since the late-time light curve is detected in K band but not in R band (see their figure 2 of Smith et al. 2008). Specifically, Smith et al. (2008) argue that the dust is in a shell of $\sim 10M_\odot$
ejected 1500 yrs prior to the SN. Since the late-time light curve is smoothly decreasing with time, rather than a burst, we instead propose that the dust is ambient in the interstellar medium within a few pc of SN2006gy. From the late-time luminosity, using a gas-to-dust ratio of 100, we estimate a local gas number density of $\sim 20 \text{ cm}^{-3}$ is enough to explain the late-time tail. If the late-time light curve is due to dust, the relative brightness in K and H band would not measure the temperature evolution of the ejecta but rather measure the temperature of the dust.

4. Supernovae SN2005gj and SN2005ap

The light curve of SN2005gj is the second brightest SN ever observed showing similarities to SN2006gy. Its light curve rose more quickly and to a higher peak luminosity than typical SNe, and declined much more slowly (Aldering et al. 2006). They are both classified as hybrid (i.e. a mixture of Type Ia and Type IIn spectra). While it has been argued that its brightness might be a consequence of a strong interaction between the SN ejecta and the CSM, no X-ray (Immler et al. 2005) and radio (Soderberg & Frail 2005) have been detected. Applying our model to this candidate shows encouraging results as can be seen from Figure 2 where the $i$-band lightcurve from our model is compared to the observed one. We assumed that SN2005gj progenitor is similar to that of SN2006gy ($M_{\text{ej}} = 60 M_\odot$, and $R_0 = 10 R_\odot$) and that the QN features are also the same ($v_{\text{QN}} = 6000 \text{ km s}^{-1}$ and $T_{\text{QN},0} = 0.4 \text{ MeV}$). The fit was obtained for $t_{\text{QN}} = 10$ days (i.e. the neutron star turned into a quark star sooner than in the SN2006gy) and by taking a slightly different range in ejecta speed, $750 \text{ kms}^{-1} < v_{\text{SN}} < 4100 \text{ kms}^{-1}$ (probably due to small differences in SN progenitor or environment). Further monitoring of the SN2005gj in the $i$-band should help distinguish between our model and those proposed in the context of CSM interaction (e.g. Chugai & Yungelson 2004; see also Figure 5 in Aldering et al. 2006).

SN2005ap has just come to our attention as possibly being the brightest SN supplanting SN2006gy (Quimby et al. 2007). Contrary to SN2006gy and SN2005gj this candidate shows a rapid decline in its light curve. As a further test of our model, we apply it to this recently discovered SN. The spectrum of SN2005ap shows velocities greater than $\sim 23000$ km s$^{-1}$, much higher than SN2006gy and SN2005gj, indicating very high QN shock velocity. Assuming a similar progenitor as for the other candidates, we obtain a remarkably good fit to the light curve for a QN delay of $t_{\text{QN}} = 40$ days and $v_{\text{QN}} = 25000 \text{ km s}^{-1}$ (see Figure 2). In this case a spherical SN ejecta ($\sim 15\%$ asphericity, based on our models) works well. In the dual explosion picture we present here, the longer the delay the lower the density of the inner edge of the SN ejecta when it is shocked by the QN ejecta. Thus we expect a higher QN shock velocity for longer QN delays, which seems to be the case for SN2005ap.

5. Discussion and conclusion

We have applied our model to the three most luminous SNe: SN2006gy, SN2005ap, and SN2005gj. The difference in parameters are the range in $v_{\text{SN}}$ and the time delay $t_{\text{QN}}$. One naturally expects variation in $v_{\text{SN}}$. For $t_{\text{QN}}$, the derived values range from 10 to 40 days, much longer than the dynamical timescale of a compact object. However, the time delay between the SN and the QN is controlled by spin-down and the increase in core density of the neutron star (Yasutake et al. 2005; Staff et al. 2006), and secondly by the weak conversion between quark flavors (e.g. Bombaci et al. 2004). The core density of the neutron star first needs to reach deconfinement density (i.e. conversion from hadrons to up and down quarks). Then weak conversion processes convert the (u,d) core to strange quark matter (u,d,s).

The spin-down delay to deconfinement density can range from less than one day to $\sim 1000$ years; the subsequent weak conversion delay is currently unknown. Our three derived total delay times were 10, 15 and 40 days. Since the total delay is the sum of a universal weak delay plus a variable spin-down delay, we constrain the weak delay to be less than 10 days.

Yasutake et al. (2005) and Staff et al. (2006) have determined that the evolutionary transition from rapidly rotating neutron stars to quark stars due to spin-down can lead to an event rate of $10^{-5} - 10^{-6}$ per year per galaxy. Similar rates were derived from studies of QNe contributions to r-process material in the Galaxy by Jaikumar et al. (2007) who estimated that 1 out every 1000 neutron stars might have undergone a QN. Since the Galaxy likely contains about $10^8$ neutron stars this suggests an average QN rate of $10^{-5}$ per year per galaxy. Interestingly, the fraction of SN progenitors with mass greater than $60 M_\odot$ can be estimated as $\sim 5 \times 10^{-3}$, using the Scalo (1986) initial mass function for $M > 8 M_\odot$. Using a SN rate of $\sim 10^{-2}$ per year per galaxy, we get $5 \times 10^{-5}$ per year per galaxy for the explosion rate of massive star ($> 60 M_\odot$). This is, within uncertainties, the same as the QN rate.

Our model suggests that the lightcurve of SN2006gy is mainly due to shock radiation from a delayed explosion inside an expanding SN ejecta of mass of $60 M_\odot$. To obtain the necessary peak luminosity for SN2006gy the second shock must reheat the SN ejecta to $\sim 0.4 \text{ MeV}$ and the reheating must occur at a large radius to minimize adiabatic expansion losses. The required energy for the reheating by the second shock is characteristic of a typical QN explosion. The $\sim 15$ days delay time is derived by fitting the light curve. In principle, the conversion delay time is not well constrained by theory since: (i) the spin-down delay depends on unknown initial spin-period and mass; (ii) the conversion process is very complex involving more than just weak processes. In fact, fitting the light curves of extreme SNe may give a means of inferring the microphysics of neutron to quark transition. To summarize, larger luminosities are obtained for reduced adiabatic losses which depend on the radius at which the QN shock breaks out of the ejecta. This can occur if the QN delay is long and the QN shock moves rapidly through the ejecta, or if the delay is short and the QN shock moves slowly through the ejecta so it takes a long time to break out.

Furthermore, if the SN ejecta density is high enough (i.e. $t_{\text{QN}}$ is small), the high temperature of the QN shock can process $^{12}\text{C}$, $^{16}\text{O}$, $^{28}\text{Si}$ and $^{24}\text{Mg}$ into $^{56}\text{Ni}$. This might provide late time emission which could explain the plateau beyond 200 days for SN2006gy, which also may occur for SN2005gj (al-
though we favor dust emission as the driver of the late-time light curve; see §3.2). In contrast, we do not expect much extra $^{56}\text{Ni}$ production for SN2005ap given its long QN delay. Finally, we mention that the neutron-rich QN ejecta is converted to r-process elements beyond $A = 130$ which may be visible in the late time spectra of SN2006gy – these nuclei and the associated observable $\gamma$-ray flux is tabulated in Jaikumar et al. (2007). Specifically, the photon flux from $\gamma$-decay of certain heavy r-process nuclei can act as tags of the QN, differentiating them from PISN (due to the lack of neutron excess) or core-collapse (lower neutron excess than the QN ejecta) alternatives. Finally, we note that the QN explosion provides enough energy (up to $10^{53}$ ergs) to power SN2006gy, while the PPISN model (Woosley et al. 2007) second explosion provides $6 \times 10^{50}$ ergs which was artificially increased by a factor of 4 to give the SN2006gy peak (see Figure 3 of Woosley et al. 2007). In addition, the time delay between the two explosions in each model differs: 10-40 days in the QN model versus ~ 7 years in the PPISN model.

If QNe do indeed occur in the universe, as this work seems to indicate, the consequences to astrophysics in general and to high energy astrophysics in particular (e.g. Niebergal et al. 2006; Staff et al. 2007; Ouyed et al. 2007) could be tremendous.

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