Is Nova Sco 1994 (GRO 1655-40)
a Relic of a GRB?

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Abstract. We suggest Nova Sco 1994 (GRO 1655-40) as a possible relic of a Gamma Ray Burster (GRB) and Type Ib supernova (SN) explosion, showing that there is evidence both that the black hole was spun up by accretion and that there was a supernova explosion. We use the disc energy delivered from the rotational energy of the black hole to power the SN, and give arguments that roughly equal energy goes into the GRB and into the accretion disc to power the supernova.

INTRODUCTION

In this note we consider only the long term GRBs, of duration from several seconds up to several minutes. This is just the dynamical time of a He star, which we consider as progenitor.

The formation of black holes in single stars of ZAMS masses $20 - 35 M_\odot$ was proposed by Brown, Lee, & Bethe (1999). However, these do not lose their envelopes except in binaries. This latter case has been studied by Brown et al. (1999) who evolve the transient sources in this way. These have mostly low mass main sequence companions, although in two cases the companions are subgiants. In many more cases, binaries of $\sim 7 M_\odot$ black holes with companions up to nearly equal mass of the ZAMS mass of the black hole progenitors are predicted. These companions do not, however, fill their Roche Lobes, and consequently are not observed. None the less, the Wolf-Rayet progenitors of the $\sim 7 M_\odot$ black holes in these binaries offer a set of progenitors for GRB’s. They are already somewhat in rotation because of the companion star. Note that in the Brown, Lee, & Bethe (1999) scenario, their envelopes are removed only following He core burning, in the supergiant stage, so there is only a short time left in their evolution for them to lose He by wind. Thus, a substantial amount of He should be left in the W.-R., although most of it will have been burned to carbon and oxygen (Woosley, Langer, & Weaver 1993), and the explosion we describe below would be Type Ib.
The conclusion of the Bethe & Brown (1999) paper was that in order for Wolf-Rayets followed by high-mass black holes like that in Cyg X-1 to be formed in single stars, a ZAMS mass of $\gtrsim 80 M_\odot$ was necessary. This was based on the calculation of Woosley, Langer, & Weaver (1993) who used a too large mass loss rate for the He winds. These stars have been reevolved by Wellstein & Langer (1999) with lower mass loss rates, but the evolution has not been carried beyond the carbon-oxygen core stage, so we do not yet know how much the lower winds will decrease the mass limit for evolving into a high-mass black hole. The carbon oxygen cores still have about 33% central carbon abundances, so they clearly will not skip the convective carbon burning stage and therefore may well end up as low mass compact objects. These high mass Wolf-Rayet stars are the progenitors of GRBs in Woosley’s Collapsar model (MacFadyen & Woosley 1999).

In addition to these and the high-mass black holes in the transient sources, the coalescence of the low-mass black holes in the Bethe & Brown (1998) scenario of compact binary evolution with the companion He star (Fryer & Woosley 1996) offers another type of generator for the long term GRBs.

All three of the above possibilities involve a He star being accreted by a black hole. In this process the black hole will be spun up. The energy can be extracted by the Blandford-Znajek (BZ) 1977 process, as in Lee, Wijers, & Brown (1999). The BZ power supplied into the disc will halt the inflow, and later propel the matter outwards (Brown, Lee, Lee, & Bethe 2000) in a Type Ib supernova explosion.

### ENERGETICS OF GRBS

The maximum energy that can be extracted from the BZ mechanism (Lee, Wijers, & Brown 1999) is $E_{\text{max}} = 0.09 M_{\text{BH}} c^2$. For a $7 M_\odot$ black hole, such as is found in Nova Sco 1994, $E_{\text{max}} \approx 1.1 \times 10^{54}$ ergs. The black hole is first formed with a mass of at least $1.5 M_\odot$ (Brown & Bethe 1994). The maximum energy, after these corrections, is still an order of magnitude greater than the $3 \times 10^{52}$ ergs used by Iwamoto et al. in the supernova explosion. Presumably the explosion will take place before the BZ mechanism can deliver full energy, leaving the black hole with substantial spin energy.

Without beaming, the estimate of the energy in the jet of the GRB (Anderson et al. 1999) is $E_{990123} = 4.5 \times 10^{54}$ ergs. The BZ scenario entails substantial beaming, so this energy should be multiplied by $d\Omega / 4\pi$, which may be a small factor $\sim 0.01$. The BZ power can be delivered at a maximum rate of

$$P_{\text{BZ}} = 6.7 \times 10^{50} \left( \frac{B}{10^{15} \text{G}} \right)^2 \left( \frac{M_{\text{BH}}}{M_\odot} \right)^2 \text{erg s}^{-1}.$$ (1)
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Several characteristics of Nova Sco 1994 (GRO 1655-40) can be understood if it is a relic of a GRB. First of all the high space velocity $-150 \pm 19$ km/s can be understood if a supernova explosion is associated with black hole formation (Brandt et al. 1995, Nelemans et al. 1999).

In our scenario, first a GRB is initiated by the BZ-mechanism, following which a Type Ib supernova explosion is begun by the energy deposited in the fat accretion disc. Following Brandt et al. (1995) we note that a binary symmetric in the frame of the exploding star will be asymmetric in the center of mass of the binary. The amount of mass that can be ejected is constrained by the fact that if more than half of the total initial mass is ejected, the system will become unbound. Brandt et al. consider collapse to a $4M_\odot$ black hole; then at the time of collapse the collapsing He star must have a mass of $\sim 9M_\odot$ or greater.

In fact, the initial black hole needs to be no more than $\sim 1.5M_\odot$ according to Brown & Bethe (1994), but one would expect a substantial amount of the carbon-oxygen core to collapse with the Fe, and also substantial fallback of the original carbon-oxygen core, probably burned to Fe in the explosion. In order to obtain an $\sim 7M_\odot$ black hole, the initial He envelope would have to be $\sim 15M_\odot$ corresponding to a ZAMS mass of $35-40M_\odot$.

Israelian et al. (1999) find a large overabundance of oxygen, magnesium, silicon and sulphur in the F3-F8 IV/III companion star of $1.6-3.1M_\odot$ orbiting the companion. These are just the elements copiously produced in a Type Ib supernova explosion. Contrary to Iwamoto et al. (1998), who need $0.7M_\odot$ of $^{56}Fe$ to reproduce the brightness of SN 1998bw, Israelian find no enhancement in the Fe. In our scenario we expect the jet of the GRB preceding the supernova explosion to go along the rotation axis of the black hole, and the supernova explosion to be initiated perpendicular to this in the accretion disc. The highly nonequilibrium processes in the jet would not initially affect the supernova, but might be expected to excite the He lines in later stages where the expanding supernova interacts with the jet.

There are indications that the black hole in Nova Sco 1994 is spinning rapidly (Sobczak et al. 1999, Gruzinov 1999). We would expect the BZ central engine to stop delivering energy following the supernova explosion which disrupts the magnetic fields.

In Appendix C of Brown, Lee, Wijers, & Bethe (1999) the observed GRB rate at the present time is estimated to be $\sim 0.1$ GEM (Galactic Event per Mega year). With a factor of 100 for beaming, this would require 10 GEM. Brown, Lee, & Bethe (1999) estimate the birth rate for visible transient sources in the Galaxy to be 8.8 GeM. However, including the high-mass black-hole binaries with companions which have not evolved to their Roche Lobes, and therefore would not be visible, they arrive at a 25 times higher number; namely 220 GEM. (Inclusion of the “silent” binaries effectively removes the $q$, the ratio of masses, in the calculation. The more massive companions are all inside of their Roche Lobes, except for the two subgiants
in the systems V404 Cyg and XN Sco.) Also, there are the other possible GRB progenitors, Collapsars and coalescing black hole and He star, mentioned above. Thus, there must be other severe criteria for GRBs; e.g., high magnetic fields in the rotating He envelopes, etc.

In evolution of the transient sources the hydrogen envelope of the massive star must be taken off only following He core burning, if collapse into a high-mass black hole is to be obtained (Brown, Lee, & Bethe 1999). In this rather last stage the companion star would try to spin the hydrogen envelope up towards corotation in the binary before expelling it. With the large viscosity from magnetic turbulence assumed in the Spruit & Phinney (1998) argument, the He core would be carried along, but probably in differential rotation because the common envelope time is very short, \( \sim 1 \) year.

Similar considerations follow for the Fryer & Woosley (1998) model of coalescence of black hole with companion He star. The common envelope evolution here need not happen as late as in the transient source scenario, but on the other hand the predicted merger rate is high, 380 GEM (Brown, Lee, Wijers, & Bethe 1999).

**DISCUSSION**

We suggested Nova Sco 1994 (GRO 1655-40) as a relic of a GRB and Type Ib SN explosion.

Our model begins from a black hole in a He star. It is assumed that in the hypercritical accretion, the disc has a high magnetic field. The black hole is spun up and the GRB, powered by the Blandford-Znajek mechanism, is driven along the nearly matter-free axis of rotation of the black hole. With high viscosity such as follows from magnetic turbulence, the swallowing of the He star by the black hole takes a dynamical time of the star. The BZ mechanism stops once the accretion disc disappears and the magnetic field disperses, leaving the black hole with some spin energy.

We point out that power roughly equal to that driving the GRB will be delivered into the disc made up out of hyperaccreting helium. The delivered energy first brings the accreting matter to rest, then drives it backwards through the accretion disc (and to the sides of it) in a Type Ib supernova explosion. From consideration of energetics, both the GRB and SN explosion can be powered by several times \( 10^{53} \) ergs, if we take the black hole to have mass \( \sim 7M_\odot \) typical of those in the transient sources, but the GRB may well take off and the explosion begin before maximum energy is delivered.

In a more detailed paper (Brown, Lee, Lee, & Bethe, 2000), we show that hypercritical accretion onto a black hole in the middle of a self-similar accretion disc of Narayan & Yi (1994) type will spin the black hole up to \( \gtrsim 90\% \) of maximum, so that \( \sim 10^{54} \) ergs is available. Running the plasma current through a current (Thorne 1986) around the black hole and through the accretion disc, we argue that roughly equal fraction of this energy are available to power the GRB and the Type
Ib supernova, the former by energy delivered in the loading area up the rotation axis of the black hole and the latter in the accretion disc. In a more detailed paper (Lee, Brown, & Wijers 1999) we show that how the plasma can pass through magnetosonic points, etc.

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