A White Dwarf Merger Paradigm for Supernovae and Gamma-Ray Bursts

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ABSTRACT

Gamma-ray bursts can appear to be a hundred times as luminous as supernovae, but their underlying energy source(s) have remained a mystery. However, there has been evidence for some time now of an association of gamma-ray bursts with supernovae of Type Ib and Ic, a fact which has been exploited by a number of models, to explain the gamma-ray burst phenomenon. Here we interpret the results of basic observations of SN 1987A and of pulsars in globular clusters, to propose the energy source, which powers at least some long-duration gamma-ray bursts, as core-collapse following the merger of two white dwarfs, either as stars or stellar cores. The beaming and intrinsic differences among gamma-ray bursts arise, at least in part, from differing amounts and composition of the gas in the merged stellar common envelopes, with the more energetic bursts resulting from mergers within less massive envelopes. In order for the beams/jets associated with gamma-ray bursts to form in mergers within massive common envelopes (as with SN 1987A), much of the intervening stellar material in the polar directions must be cleared out by the time of core-collapse, *or* the beams/jets themselves must clear their own path. The core-collapse produces supernovae of Type Ib, Ic, or II (as with SN 1987A, a SNa IIp), leaving a weakly magnetized neutron star remnant with a spin period near 2 milliseconds. There is no compelling reason to invoke any *other* model to account for gamma-ray bursts. Far from being an unusual event, SN 1987A is typical, having the same merger source of initiation as 95% of all supernovae, the rare exceptions being Ia's induced via gradual accretion from a binary companion, and Fe catastrophe II's.

Subject headings: gamma rays: bursts — globular clusters: general — pulsars: general — supernovae: general — supernovae: individual (SN 1987A) — white dwarfs

1. Introduction

Gamma-ray bursts (GRBs) were discovered over three decades ago (Klebesadel, Strong, & Olson 1973), with two distinct temporal classes emerging: short and long, with distributions centered near 0.3 and 20 s, being nearly separated at $t = 2s$, and having larger and smaller hardness ratios respectively (Paciesas et al. 1999), though with nearly 50% overlap (Kouveliotou et al. 1993). That longer duration GRBs at cosmological distances should be associated with fading afterglows was predicted a decade ago (Paczyński & Rhoads 1993; Katz 1993), and confirmed more recently in the optical and X-ray bands, as for GRB 970508 (Costa et al. 1997; van Paradijs et al. 1997), and later in the radio, as for GRB 970703 (Frail et al. 1997). The identification and redshift determination of the host galaxy for GRB 970508 definitively confirmed its extragalactic nature (Metzger et al. 1997). The next year Galama et al. (1998) found the Ic SN 1998bw within the error circle of GRB 980425 (Pian et al. 1999). Just afterward Bloom et al. (1999) measured a possible SNa Ic component in the fading afterglow of GRB 980326, which led to other such possible associations, as for GRB 970228. That GRB 980425 was four orders of magnitude less luminous than typical cosmological bursts and the low redshift of SN 1998bw (0.0085), led to widespread skepticism of this association (Wheeler 2000). Recently, however, the case for a SNa-GRB association has been bolstered by the association of GRB 030329 with SN 2003bh (Hjorth et al. 2003).

Supernovae are generally classified according to their spectra, Type II for those with hydrogen lines and Type I for those without (Filippenko 1997). These are each further divided into three subclasses, with Ia's showing strong Si lines in their early spectra, indicating a thermonuclear runaway of a white dwarf star, while Ib's show helium, and Ic's neither hydrogen nor helium, but intermediate mass elements instead. Ib's and Ic's are thought to share core-collapse as a common cause with all Type II's, except that their progenitors have been stripped of hydrogen (Ib), or both hydrogen and helium (Ic). Ia's also differ from Ib's, Ic's, and II's, in their luminosities, in some cases producing, via C-O burning, nearly a solar mass of ^{56}Ni – ten times the amount typical of all other types of SNe.

A number of models have been proposed to explain GRBs. Some earlier ones, which may not survive a GRB-SNa association, invoke neutron star (NS) collisions with other NSs or black holes (BH) (Lattimer & Schramm 1974; Eichler et al. 1989; Narayan, Paczyński, & Piran 1992). Other, more recent models produce SNa-like explosions by invoking collapses of massive stars, into magnetars (Wheeler et al. 2000), and black holes: with strong magnetic fields via "hypernovae" and "supranovae" (Iwamoto et al. 1998; Vietri & Stella 1999), and without, via "collapsars" (MacFadyen & Woosley 1999).

This paper shows that a conceptually very simple model involving the merger of two white dwarfs (WDs), as cores of massive stars or not ("double degenerate"), satisfies the observational constraints of long duration GRBs and most SNe well, while others fall short of this goal.

2. Background

In 1987 my colleagues and I discovered the first pulsar in a globular cluster (GC), with a period of 3 milliseconds (Lyne et al. 1987). It soon became clear that there were many more millisecond pulsars (MSPSRs) in the GCs than their supposed progenitors, the X-ray binaries, could account for under the standard "recycling" theory (Alpar et al. 1982), by about a factor of 100 (Chen, Middleditch, & Ruderman 1993, hereafter CMR). In recycling, an ancient, solitary, slowly-spinning NS is spun up by accretion from a captured companion. In spite of more than 16 years of effort, recycling has not yet successfully accounted for the GC MSPSR population. The most careful treatment of this issue confirmed that there had to be a mechanism, other than (gradual) post-collision accretion, either from companions or disruption disks, which could form weakly magnetized, rapidly-spinning MSPSRs (Bailyn 1996).

The only other way to get a WD in a GC, with a mass exceeding the Chandrasekhar limit of 1.4 solar, is to merge two (or more) WDs (Chen & Leonard 1993). If core-collapse via merger is possible, then formation of MSPSRs via merger, particularly with *each* having a binary companion, almost always dominates recycling. This is due in part because the cross section for binary-binary collisions is always larger than those of the binary-single, and, *a fortiori*, the single-single collisions, necessary for the isolated NS star to capture a companion from which to eventually accrete matter. Since the number density of binaries is approximately equal to that of isolated stars, the inequality of cross sections applies to collision rates as well. Moreover, each of the *two* stars left over from the binary-binary merger process could persist as post-SNa binary companions, consistent with the high incidence of binarity among MSPSRs. The recycling yield for MSPSRs may also be low, relative to the merger yield, because evolution, accretion, and spinup must follow the capture, as opposed to just core-collapse following merger.

The same year also saw the SN 1987A outburst, followed shortly by the discovery of the "mystery spot" (Meikle, Matcher, & Morgan 1987; Nisenson et al. 1987). There is now evidence for two spots (Nisenson & Papaliolios 1999) on opposite sides of, and in line with, the axisymmetric ejecta (Wang et al. 2002). The closest spot was $\sim$0.06 arc s south of SN 1987A (17 light days in projection), and had a luminosity nearly 5% of maximum light (3×10^{42} ergs/s, 8×10^{8} $L_{\odot}$, or magnitude 5.7 vs 2.5 at 6585 Å). Like the overabundance of MSPSRs in the GCs, this feature has never been reconciled with traditional models (of

SNe).

3. The Paradigm for SN 1987A

When the structure and kinematics of the inner ring surrounding SN 1987A became clear almost a decade ago (Jakobsen et al. 1993; Plait et al. 1995; Burrows et al. 1995), other colleagues proposed a binary merger scenario (Chen & Colgate 1994). In this picture, the inner ring was formed by mass loss through at least one of the two outer mass axis Lagrangean points (L2 & L3), efficiently producing its extremely low 10 km/s expansion velocity (as compared to blue supergiant (BSG) winds), essentially the thermal velocity of hydrogen at photospheric temperatures (Lubow & Shu 1976). The polar gradients of the potential just beyond L2 and L3, may have helped collimate the gas outflow to the observed small inner ring angular height. Neither member of the close binary was likely to have had a recent red supergiant wind due to limitations of space.

The two fainter, outer rings around SN 1987A were formed close to the epoch of the contact binary during which the inner ring was formed, as all three are expanding homologously (Crotts & Heathcote 2000). Radiation pressure from one or both stars on their companion's outer atmosphere may have produced the wind of $\sim$25 km/s, least disturbed by the orbital motion for the two directions, nearest to, but at least 30 degrees from, their respective poles (Chanan, Middleditch, & Nelson 1976). The actual half angle of each cone, formed by the outer rings with the stellar remnant, which perhaps could be used to determine the pre-merger mass ratio, is a more realistic 48 degrees, with the flow, over the whole domain of polar angles, forming the observed fans of extended emission (Burrows et al. 1995). Finally, the lower nitrogen abundance, relative to that of the inner ring (Panagia et al. 1996), indicates a more superficial (and/or selective) source than Roche lobe overflow, for the gas in the outer rings, consistent with the wind hypothesis.

4. The Paradigm for the General WD-WD merger

As the WD cores move closer to each other in their decaying orbits within the common envelope, the shape of that envelope must transition from bi-lobed to spheroidal. Thus, for a brief period, the nearly merged star was likely to have been concave in both polar directions, but still later convex. The transition between the two geometries may cause polar ejection of material, that we can speculate formed the target into which a polar beam/jet dumped (an isotropic) 10^{49} ergs *en passant* (Meikle et al. 1987). To be conservative, the spot is assumed *not* to be material traveling at relativistic speed, prior to being hit by the beam/jet, which *was* relativistic (Nisenson & Papaliolios 1999).

Just prior to core-collapse, angular momentum transfer from the two merging WD cores might have at least partially cleared out the star's inner polar regions. Having the SNa-associated beam/jet itself blast through, or carry along, the normally intervening stellar material, seems improbable. The pre-SNa clearing process may expose the hotter interior of the star to the outside world. If this exposure is sufficiently abrupt, the increase of apparent mean temperature and luminosity of the star could be exploited to form an "early warning system" for merger SNe in most of the BSGs in the Local Group and blue stragglers in the globulars. It must, however, be followed promptly by core-collapse so that nearby material doesn't close in again.

The merged WD would rotate with a period near 1.98 s, set by the branching between Jakobi and Maclaurin configurations (Chen & Colgate 1994), and, if its mass exceeded 1.4 solar, core-collapse would follow in many (Saio & Nomoto 1998) or most cases. A NS/pulsar with a spin period near 2 ms would form within a Type Ib, Ic, or II SNa, consistent, in the case of the IIp SN 1987A, with the 2.14 ms signal (Middleditch et al. 2000, hereafter M2000).

5. Discussion

It has already been suggested that the mystery spot in SN 1987A, about 24 light days distant from the pre-explosion binary's pole, was a result of a lateral GRB (Cen 1999). But the crucial link to understanding GRBs may be that most Type Ib, Ic, & II SNe, which may comprise more than 90% of all SNe, are the result of WD-WD mergers. Since, as we have argued, SN 1987A was the result of such a merger, and certainly produced a NS (Bionta et al. 1987; Hirata et al. 1987), then we know that such mergers can indeed produce NS remnants, which can also be MSPSRs (M2000). The vast overabundance, and other details of the MSPSRs in the GCs (CMR), including the 2.1 ms minimum period (Camilo et al. 2000), strongly support this assertion.

The recent discovery of five transient X-ray MSPSRs (TXRMSPs) in the Galactic plane (Wijnands 2003) does not challenge this view. The same mechanism, which likely produces most of the binary and solitary MSPSRs in the globulars, works at least as well as recycling (see above), even in the Galactic plane. The discovery of more TXRMSPs in the Plane, without any in the GCs, may indicate that the companions, whose evolution drives the transient accretion, are not common among the offspring companions to the MSPSRs produced by mergers in the GCs. The magnetic fields of the NSs associated with TXRMSPs (Psaltis & Chakrabarty 1999) may also be larger than the 10^{8-9} G typical of the MSPSR fields in the GCs. Either way, the situation is becoming embarrassing to the application of recycling everywhere, all the while not even exclusively supporting recycling in the Plane.

Core-merger for SNe engenders a natural beam/jet collimation mechanism and, in doing so, produces an axisymmetric SNa, consistent with SN 1987A (Wang et al. 2002), and the significant polarizations observed in SNe (Leonard et al. 2000; Wang et al. 2001). It also doesn't suffer from the difficulty that plagues the massive star-black hole models, in producing the apparent maximum energy observed in the radio lobes (Frail et al. 2001). The less massive common envelopes in such mergers may result in more energetic GRBs and less highly collimated beam/jets, as they are both easier to break through, and to accelerate in part, hence the association with SNe Ib's and Ic's. However, it is not yet clear how much collimation is due to the merging cores or to the stellar interior external to them. The GRB rate of 1.8×10^{-10}/yr/Mpc^3 (Schmidt 1999), and the SN Ib,c rate of 3×10^{-5}/yr/Mpc^3, can be reconciled if each pole of the merger has a beam/jet collimated to a 0.5 degree diameter (Lamb, Donaghy, & Graziani 2003b). The metallicity of the common envelope may also affect the GRB's.

Unlike most Type Ib and Ic SNe, the beam/jet from SN 1987A entrained and/or encountered a much higher density of material, and thus may have been attenuated so that radio lobe formation did not occur (as these were not detected), or what radio emission was generated may have been absorbed or beamed. However, simple plasma absorption for radio frequencies from 1 to 40 GHz would require a free-electron density of $\sim 10^{10-13}$ cm^{-3}, but this may to be too high to achieve (the number density of the inner ring is $\sim 10^4$ cm^{-3}). Synchroton self-absorption also may not occur, though the issue is highly complex.

Beaming, in general, removes the 10^{54} erg energy requirement for GRBs that hypernovae, supranovae, collapsars, and other models were proposed to satisfy (Iwamoto et al. 1998; Vietri & Stella 1999; MacFadyen & Woosley 1999). The vast majority of Type Ib and Ic SNe, which show no evidence of the central engine as was associated with SN1998bw (Berger et al. 2003), near GRB980425 (Kulkarni et al. 1998), may also have had more massive common envelopes, and/or radio lobes hidden by beaming, with the additional caveat that perhaps not all Type Ib and Ic SNe result in a NS remnant. The yield can not be so low, however, as to deprive the GCs of their quota of MSPSRs.

The extremely high expansion velocities seen in SNe associated with GRBs (Iwamoto et al. 1998), may be due to less massive/lower metallicity common envelopes. Likewise, the suggested correlation between the isotropic GRB energy with distance (Lamb et al. 2003a), if real, could also be a due to lower metallicity in the earlier common envelopes. Although the magnetic fields resulting from merger are typically low (few$\times 10^9$ G – M2000), these will likely have some effect on the beam/jet. Additional energetic events following the initial burst could simply be due to the beam/jet hitting other gas targets farther away in the polar directions of the binary merger. GRBs which are *preceded* by SNe, as might be the case for GRB 021211 (Della Valle et al. 2003), could have been produced by a beam/jet, which was slightly off our line of sight, hitting such a target.

Finally, magnetars, NSs with magnetic fields as high as 10^{16} gauss, which are supposed to drive the GRB/SNa explosion (Wheeler et al. 2000), are observationally constrained during the SNa decline (Middleditch & Kristian 1984), and later (as in Cas A – Chakrabarty et al. 2001) by the expected X-ray modulation of the still hot NS, via residual accretion or magnetic-thermal interaction. These would otherwise be an observer's dream, shining through the opacity from time to time, all the while slowing down dramatically. The nearby reality, however, is far different, with SNe fading time after time, like SN 1987A, at least as rapidly as the ^{56}Co decay curve for the first few years, with rare exceptions likely only due to circumstellar material. The magnetar hypothesis can only be made viable, for the vast bulk of SNe, by the most arduous fine tuning of spin frequency and remnant opacity history.

The issue of whether most SNe Ia also result from merger is beyond the scope of this work. There could be enough such mergers, with sufficient total mass, to account for all SNe Ia (Liebert, Arnett, & Benz 1997), unless most of these result in core-collapse. Thermonuclear runaway, however, could produce overluminous SNe Ic with the usual lines from intermediate mass elements – objects which have never been observed. Thus, unless these *never* happen, which seems unlikely, such mergers *always* produce core-collapse, *or* by the time of the thermonuclear runaway most of the intermediate mass elements have already been consumed. There is no constraint on the delay between merger and runaway. In spite of the recent detection of hydrogen lines in the field of SN 2002ic (Hamuy et al. 2003), the science of SNe Ia's remains in the Dark Ages.

6. Conclusion

We have shown that a very simple model for binary WD-WD merger explains the details of the axisymmetric remnant expanding from, and the ringed gas structure surrounding, SN 1987A (Chen & Colgate 1994), as well as the apparent 2.14 ms pulsar signal for the compact remnant (M2000). By extending this picture to other Type II, as well as Type Ib and Ic supernovae, which comprise at least 90% of all SNe, we have accounted for the anisotropies recently discovered in many other SNe, as well as all of the fundamental details of long-duration GRBs. At this point, other models to explain this class of GRBs appear to be superfluous.

The nature of the energy source behind GRBs can *definitively* be confirmed only, perhaps, for pulsars, from magnetars to MSPSRs, by detecting an underlying periodicity. Thus, taking "imposter" SNe into account, high time-resolution observations of *all* nearby (< 50 Mpc) SNe should be made, using the largest and most sensitive optical and radio telescopes, to search for pulsar remnants. Unlike SN 1987A, opacity will not be an issue for many of these. Observations of only SNe which happen to be associated with GRBs might not be fruitful, as these are usually much farther away, and the proximity of the line of sight to the rotation axis of the binary merger could reduce the amplitude of the pulsar signal.

Although a number of extragalactic SNe (but no Ib's or Ic's) have already been searched (Middleditch & Kristian 1984), and this has continued sporadically, without success, only scant resources have been devoted to this effort so far. Continuing indefinitely *without* making further, more sensitive searches, is to risk wasting time and resources. The results from SN 1987A, now less controversial due to strong evidence for precession in two other "normal" pulsars, B1828-11 and B1642-03 (Stairs, Lyne, & Shemar 2000; Shabanova, Lyne, & Urama 2001), imply a pulsed optical signal of 10 or more solar luminosities, at 5.0 – 6.5 years of age (M2000). This is hardly surprising, as the Crab pulsar's (nearly entirely pulsed) optical output is 4 solar, and nanosecond radio bursts in pulsars are bright enough to be seen in neighboring galaxies (Hankins et al. 2003).

This new understanding of GRBs and SNe may represent the end of an era, begun four decades ago, of exploration and discovery in high-energy astrophysics. The core-collapse events, and early stages of the 2 ms pulsar remnants from SNe in the Local Group, may be detectable by gravitational wave detectors such as LIGO (Santostasi, Johnson, & Frank 2003), provided an early, rudimentary spin frequency history can be obtained by detecting the pulsars in other bands, such as the optical and/or radio. Thus this new understanding also *begins* an era, which will span the first part of our own 21^{st} Century, of extragalactic pulsar astronomy.

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