Predicting the next local supernova

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Abstract

Core collapse within blue supergiant stars, as occurred within Sk -69°202/Super nova 1987A, is generally attributed to a merger of two electron-degenerate cores within a common envelope, with a merged mass in excess of 1.4 solar. Supernova 1987A also had two associated bright sources, one with about 8% of the Hα flux, and 74 milli-arc seconds distant by day 50, and another, four times fainter and 160 milli-arc seconds away in the opposite direction on day 38, when the first bright source was only 60 mas distant. Using recent advances in our understanding of pulsars, we can show that the second source was the result of the core-merger process, which can drive a relativistic jet of particles prior to the completion of the merger process, whether this proceeds to core collapse, or not. As with those resulting from core-collapse, such beams and jets are likely to produce an obvious spectral signature (e.g., even in un-red/blueshifted Hα), which can be detected in nearby galaxies. There is very likely a time interval of a few months, during which such supergiant stars, a high fraction of which will eventually undergo core collapse, can be identified. These can be carefully followed observationally to maximize the chance of observing core collapses as they happen. Such studies may eventually help in using such objects as standard candles.
I. INTRODUCTION

As recently as 1987, orthodox supernova theory did not anticipate that a star could undergo core collapse while it was a blue supergiant – only during the supposedly later red supergiant phase was this expected. On 23 February, 1987, Supernova 1987A in the Large Magellanic Cloud, the offspring of the blue supergiant star, Sk -69°202, changed that expectation. The simplest explanation for this is that Sk -69°202 was, in fact, a star with two electron degenerate stellar cores within a common envelope (in isolation these would be white dwarf stars) which were about to merge.¹,² The observation of a 2.14 ms signal from SN 1987A in the optical/near-infrared, over a timespan of four years, is consistent with this process, as is the 0.62 foe energy drop from an initial spin period of 2.00 ms.³–⁵

The merger was the result of a binary stellar system close enough so that the friction of the motion of the binary components within the expanding stellar envelopes was sufficient to cause the orbits of the cores to decay, moving closer to their companion with time. There is plenty of other evidence for binarity in the progenitor, including the rings,⁶,⁷ and the mixing observed in the ejecta,⁸,⁹ but we note in [5], that the anisotropy of the expanding remnant¹⁰,¹¹ is more a result of the SN disruption process.

II. THE OBSERVATIONS

A bright source (BS1) only 45 milli-arc s (mas) from, and amounting to 8% of, the flux of SN 1987A, was observed¹² on day 30 in a 10 nm-wide filter overlapping Hα, at a bearing of 194°. By day 38 it was 60 mas away, and on day 50, 74 mas distant (still at the same bearing, and days 29.8, 37.8, and 49.8 are used for purposes of calculation).¹³ The source was not detected when it was observed again on day 98 by the first group. However an improved analysis on data from day 38, done by them a decade later,¹⁴ detected another nearby bright source (BS2), four times fainter than the first (at magnitude 8.25, still the brightest source in the LMC, other than SN 1987A proper and BS1), and 160 mas away in the opposite direction – the line joining the two contained SN 1987A proper.

The BS1 data, along with the early light curve of SN 1987A from the Cerro Tololo Inter-American Observatory (CTIO) 24-inch telescope¹⁵ and the International Ultraviolet Explorer,¹⁶ were used to solve for the offset and depth of circumpolar ejecta near Sk -69°202,
and the orientation and kinetics of a beam of radiation and jet of particles emerging from the star’s (south) polar direction.\textsuperscript{17}

The solution revealed a light beam and particle jet with a collimation factor $< 10^{-4}$, an orientation of $75.2^\circ$ (slightly pointed toward Earth, but mostly south), and $10.5/25.5$ light-days ($\ell t$-d) to the beginning/end of the circumstellar ejecta above the south pole of Sk $-69^\circ$202. The fastest particles in the jet travel at almost $0.958 \, c$, which is consistent with the kinetic energy of the peak in the proton cosmic ray spectrum near $2.-2.5$ GeV.

The only way that both BS1 and BS2 could have been the result of jets driven by post-core-collapse Sk $-69^\circ$202 (SN 1987A), was for BS2 to be approaching, in order that it not be overwhelmingly delayed, as was first noted by [14], which means the two sources and 87A would not lie on a single line. However, Occam’s razor would suggest that if BS1, 87A, and BS2 appear to be colinear in the plane of the sky, then it is most probable that they are, in fact, colinear in three dimensions, so that BS2 is slightly receding. Moreover, the solution to the geometry as done in [17] assuming BS2 came from the core collapse, as is the case for BS1, has BS1 emerging at $62.4^\circ$, still $12.8^\circ$ off the $75.2^\circ$ solution from [17], with a peak of the proton cosmic ray spectrum well beyond $2.5$ GeV (Fig. 8 of [17]), in conflict with observation.

Finally, the right triangle at day, $d = 37.8$, made from the approaching solution BS2, measured at $h$ ($45.93 \, \ell t$-d, or 160 mas) from 87A at $(0,0)$, and $(\rho - d, 0)$, has a hypotenuse of $\beta \rho$. With $\rho$ as the current radius of the first SN flash, and $\beta c$ the mean velocity for the matter swept up to form BS2, a real solution for $\rho$ occurs only if $\beta > h/\sqrt{h^2 + d^2} = 0.772$, which is highly unlikely.

Even a beam of light from the SN flash, which hit matter at BS2 in time to illuminate it at day 37.8, still requires ejection and subsequent “sweepup” of material, prior to core collapse, to form the target the beam eventually hits. It is also unlikely that scattered light alone can make BS2 as bright as observed. For all of these reasons, BS2 cannot possibly have originated from the core-collapse event. Figure 1 shows a geometry of the system (from [17]), assuming BS2, 87A, and BS1 are, in fact, colinear in three dimensions (but was calculated for day 30 instead of day 38).

Opposite sources for BS1 and BS2 have been added to Fig. 1. These have never been observed, but for good reasons. Source BS1’ suffers from greater opacity from the circumstellar material than does BS1. The breakout of the beam of light,\textsuperscript{18} i.e., the “Bochum Event” at
FIG. 1. The geometry of SN 1987A on day 18 and associated sources (at other corresponding times – [17]). Bright Source 2 on day 38 (this figure is for day 30 – top horizontal scale), was observed to be 160 mas north of SN 1987A (right hand vertical scale). The forward counterpart of Bright Source 2, BS2’, would have been observed to be 160 mas south of SN 1987A on day 14 (again top scale – this date has been corrected for BS2 at day 38). BS1’, the back counterpart of BS1, at day 21 has been arbitrarily set at 36 mas north of SN 1987A (right scale). BS1 at day 15 and BS1’ are just starting to form from the beam and jet (red) impacting the beginning of the polar ejecta (green, starting at ±10.5 ℓt-d, but graphically obscured by ejecta until after ±17 ℓt-d in projection).

day 19.2 (Fig. 5 (b) ‘E’ of [17]) attests to the significance of this opacity.

The counterpart to Bright Source 2, BS2’, would have been exactly opposite BS2 on day...
14 (top scale of Fig. 1, plus 8 to compensate for the time difference to day 38). The speckle observation sufficiently sensitive to detect it, however, was made on day 38 so BS2′ would have suffered 16 more days of fading and motion away from 87A (3.2 more ℓt-d at 0.2 c), by then, in all likelihood, invisible to any analysis. Again from Fig. 1, even corrected to day 38, it is obvious that Bright Source 2 was a result of a polar beam of light and jet of particles ejected from Sk -69°202 – the progenitor star – just as BS1 was a similar result of SN 1987A.

III. INTERPRETATION

Recent theoretical advances in our understanding of the pulsar mechanism\textsuperscript{19–24} have explained how polarization currents, induced well beyond the pulsar’s speed-of-light cylinder (and so updated in a pattern much faster than light), and within the progenitor’s plasma, will drive a highly collimated ($< 10^{-4}$) beam of light and jet of particles in the polar directions. Each annulus of polarization currents, coaxial with the star’s rotation axis, produces two focused beams, whose paths are given by

$$Z = \pm \sqrt{(R^2 - 1)(X^2 - 1 + \frac{1}{R^2})}; \quad Y = \frac{1}{R}; \quad R \geq 1$$

for a current source at (0,R,0), on an annulus in the X-Y plane centered at (0,0,0), where $R$ is the ratio of the polarization pattern update speed (in the +X direction) to $c$, and $X$, $Y$, and $Z$ are measured in light-radians of the pulsar. Thus the beams propagate in an X-Z plane with a Y-intercept of $1/R$, and their power diminishes only as $1/distance$. The larger $R$ is, the more polar the beam. Typically, $R$ exceeds 100,000 toward the equators of blue supergiants disrupted by a 500 Hz pulsar, and likewise for red supergiants disrupted by a 50 Hz pulsar (see immediately below). The asymptotic pattern of the focused radiation, from an annulus of current sources in the X-Y plane, is two circles on the sky of equal and opposite spin latitudes given by $\pm \arccos(c/v)$, where $v$ is the update speed of the polarization current pattern.\textsuperscript{5}

Just as a rotating neutron star can excite polarization currents in an annulus with a pattern which is updated faster than $c$, so can two co-orbiting C-O white dwarf cores. Their magnetic field lines will thread and behave, more or less (with spin as a wild card), as if the two cores were a single rotating, but not necessarily aligned, magnetic dipole. If
we let $r_{eq}$ represent the equatorial radius of Sk -69°202, $a$ the separation of two 0.7 M$_\odot$ electron degenerate cores, and $P$ their orbital period, ignoring the other material in the stellar interior, we have, for $R_{eq}$, the ratio of the equatorial excitation speed, $v_{eq}$, to $c$:

$$R_{eq} \equiv \frac{v_{eq}}{c} = \frac{2\pi r_{eq}}{(Pc)} = 0.4547 \left(\frac{r_{eq}/(10^7 \text{ km})}{(a/(10^5 \text{ km}))^{3/2}}\right).$$  \hspace{1cm} (2)

The equations for $P$ and $a$ are useful to have on hand:

$$a = 59,131 \text{ km} \times \left(\frac{r_{eq}/(R_{eq} \times 10^7 \text{ km})}{(a/(10^5 \text{ km}))^{2/3}}\right); \hspace{1cm} P = 460.9 \text{ s} \times \left(\frac{a/(10^5 \text{ km})}{(10^7 \text{ km})}\right)^{3/2}.$$ \hspace{1cm} (3)

The equatorial excitation velocity reaches $c$ ($R_{eq} = 1$) for $r_{eq}/(10^7 \text{ km}) = 2$, $a = 93,864$ km, and when the orbital period is 419 s (also the circumference of the star in $\ell$t-s).

Since much of the non-degenerate stellar core will rotate with the two cores, the separation between the two may not be in accordance with Eq. 2. Also in order for the beam and jet to be well collimated, we need $R >> 1$. Although the $2 \times 10^7$ km radius of the blue supergiant\textsuperscript{25} limits $R$ to be less than 210, assuming a minimum orbital period of 2 s ($a=2,660$ km), this is still sufficient to drive a highly collimated beam and jet, after first driving less collimated features (there is no precession for this process, unlike post-core collapse).

It is unclear how much of the shroud material, experienced by the post-core-collapse beam and jet, is due to the core-merger process. This complicates the estimate of the time delay between the appearance of BS2 and core collapse. If BS2 encountered as much circumstellar material as BS1 did, then, judging from Fig. 1, getting to 74 mas (all projected from 75.2°) within the polar ejecta took 50 days. There remains another 10 mas or 2.9 $\ell$t-d of polar ejecta to get through, and then another 21 $\ell$t-d at something near 0.2 c, which amounts about 171 days total (deprojecting all but the 50 days).

The continued slope\textsuperscript{5} of the early light curve after the Bocum Event suggests that there may still have been material to be swept up beyond 25 $\ell$t-d, so this “coasting” velocity may have fallen below 0.2 c. On the other hand, in the unlikely possibility that there is little polar ejecta to “bunch up,” until a target of material already at 160 mas (projected), then the extra time between merger beam and core-collapse beam would only be 25 $\ell$t-d, which deprojects to a 25.86-day interval. The physical reality is likely to be some time interval between the extremes, and five months might be a good guess. Of course this only applies to the geometry of SN 1987A – the delays to core-collapse of other systems with less oblique geometries could be much smaller.
IV. DISCUSSION

Normally, one would not expect that a large star, with two tiny cores churning deep within its center at what one would think was a lazy pace, could drive relativistic jets of particles from its poles, but that’s how the mathematics work, and in consequence, how the Universe must work (the focusing calculated in [5] is so extreme that the defocusing effects of the stellar interior are not likely to change this). In fact, **all** large stars will eventually produce polar jets as they develop rotation and magnetic fields within their core(s), whose moments of inertia drop with time due to orbital decay for doubles, and burning to heavier elements for massive singles.

Although the velocities of C or O ejected from stars without H or He, the progenitors of SNe Ia, will be less than the 0.957 c of H, they need to be at least 0.75 c if they drove the H in SN 1987A by collision, and 0.8747 c if they were all driven electromagnetically, with equal energy per proton, assuming nuclei with all of their companion electrons ionized away. However, the H driven by the pulsar companion to SS 433 is line-locked at just under 0.28 c, probably due to the absence of heavy elements.\(^{17}\)

It is unknown whether there were any recognizable H\(\alpha\) lines with up to 40\% red/blueshifts associated with SN 1987A (the 8\% in H\(\alpha\) is limited to close to \(\sim\)6561 Å, but there is still H\(\alpha\) flux well outside of this band because there are also parts of BS1 with its bulk, particle beam, and target impact velocities, among others). However the main focus back then was on a continuum of smaller shifts. Sk -69\(^\circ\)202, 50 kpc distant in the LMC, with a B magnitude of 12.28, would be 18.8 magnitudes at 1 Mpc, still enough light to get a spectrum with a big telescope.

The entire local group lies within 1 Mpc, including both M31 and M33. NGC 55, 300, and 3031 (M81) lie at 1.2, 1.3, and 1.4 Mpc respectively, and the blue supergiants in all three are still accessible. Perhaps the most interesting possibility is the ability to predict core collapse to a black hole, and the more massive, and certainly brighter supergiants likely to do this would be accessible out to 5 Mpc, which would bring NGC 253, 1313, 2403, 3034 (M82), 4449, 4736 (M94), 4826 (M64), 4945, 5128 (Cen A), 5236 (M83), 5457 (M101), 6946, and 7793 into range.

Red giants and supergiants, however, will likely have polar jets well in advance of their impending core collapse. In such stars of 20 to 25 solar masses, oxygen burning will last a
handful of months, while silicon burning will last a handful of days. In order to predict their core-collapse events in good time, we will need a way to recognize the transition to oxygen burning.

Aside from emission characteristic of a strongly magnetized young pulsar remnant in VT 1137-0337, no such central source has been detected in any other SN. This may mean that 1993J, although a SN of a red supergiant, was still due to a merger (but one with an extreme mass ratio) so that any remnant would not be strongly magnetized. The merger may have left a black hole, but it is not clear whether this would have led to a recognizable SN, as was observed. However, even such a merger within a red supergiant should still produce high velocity jets in the pre-core-collapse phase.

V. CONCLUSION

The second bright source near SN 1987A, BS2, found by [14] can only be successfully interpreted as a mildly relativistic jet of particles (and likely a beam of light) driven by the core merger process months prior to core collapse. These effects may allow the spectral identification of Galactic and extragalactic supergiants which will undergo core collapse within a few months, leading to the exciting possibility of observing core collapse as it happens. In the long term we will need to observe many more such events in the hopes that these may eventually be used as standard candles, which, at present, is impossible. There are also those events in the brightest supergiants leading to black holes, about which almost nothing is known. Given the new understanding of disruption from core-collapse developed in [5], it is not at all clear what such events would look like, as there would be no pulsar to disrupt the star.

VI. ADDENDUM

Observations of the progenitor of SN 2020tlf reported in [27] showed a roughly constant jump in luminosity for 130 days prior to core-collapse, in good agreement with the “five months” estimate, given at the end of Section III (which was conservative in the sense that slightly more time was allotted for Bright Spot 2 to reach a projected distance of 160 mas). Once the delay, between the initiation of high velocity jets (which affects the luminosity of
the common envelope star), and core-collapse, is known, aside from the size of the star, few other parameters, including the inclination wrt the Earth, should strongly affect it.

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