

Supernova Spectral Feature Addresses the Connection with Gamma-Ray Bursts

Evidence is growing that gamma-ray bursts are generated by relativistic jets of material ejected from atypically massive and energetic supernovae flattened by high spin.

It's been clear for almost a decade that the predominant class of gamma-ray bursts—the so-called classic or long-duration GRBs—are at cosmological distances. The accepted picture is that a classic GRB spews out about 10^{51} ergs (10^{44} joules) in a back-to-back pair of narrow beams of gamma radiation that typically lasts tens of seconds. Less clear is the underlying mechanism responsible for such spectacular energy release.

One much-considered mechanism has been the cataclysmic merger of a neutron star with a “compact” binary partner—a black hole or another neutron star. But that model seems to yield subsecond bursts that are too short for classic GRBs. Nor does it explain why so many GRBs are associated with star-forming regions.

More popular nowadays is the “collapsar” model introduced by Stan Woosley (University of California, Santa Barbara) in 1993 (see *PHYSICS TODAY*, July 2002, page 18). Woosley proposed that a small fraction of core-collapse supernovae would form remnant black holes and create relativistic jets of narrowly collimated ejecta that generate GRBs.¹ In recent years the theory has been bolstered by a handful of supernova sightings somehow associated with GRBs.

A core-collapse supernova occurs when a massive star (at least 8 solar masses) has consumed all the thermonuclear fuel in its core. Suddenly, thermal pressure no longer balances the star's gravity, the core collapses, and the rebound shock wave tears the star apart. The core-collapse supernovae Woosley has in mind are an atypical subset: The parent star must have unusually high spin and large mass—at least 30 solar masses. Furthermore, it must have lost its hydrogen and helium envelopes some time before the collapse.

This last requirement focuses the attention of observers on a spectroscopic subclass of core-collapse supernovae called type Ic, which are characterized by the absence of H or He lines. Of the hundreds of classic GRBs recorded in recent years, observers have been able to associate about a dozen with supernova explosions. And in each of the three cases where they

have gotten some spectroscopic handle, the supernova did indeed appear to be an unusually energetic type Ic. In trying to associate GRBs with supernovae, observers face the problem that classic GRBs are visible at much greater distances than supernovae, albeit with less precise localization on the sky. And a supernova seen in conjunction with a GRB is difficult to examine in the glare of the GRB's optical afterglow.

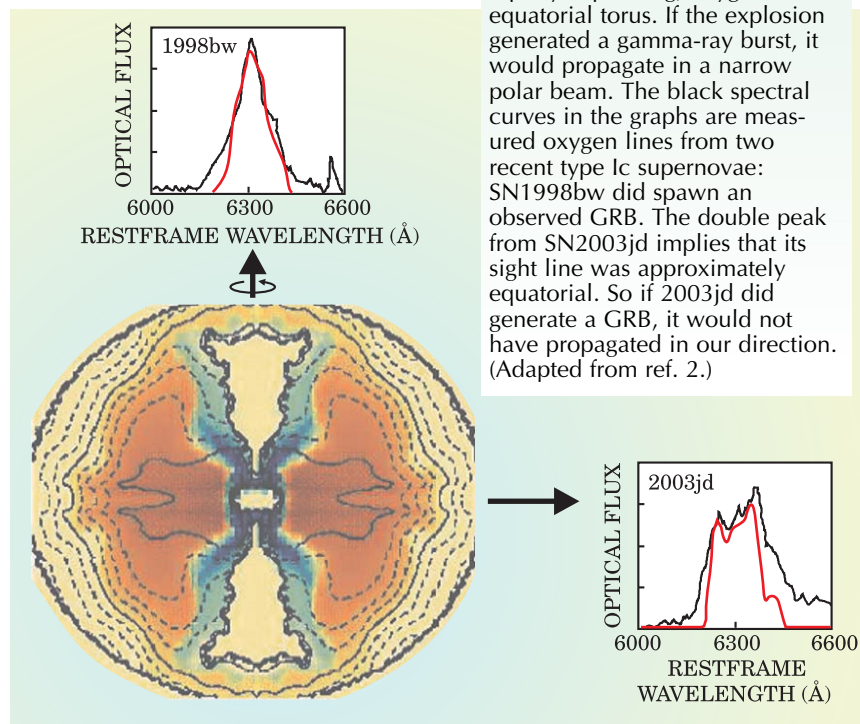
A two-horned spectrum

A recent paper by Paolo Mazzali (National Institute of Astrophysics, Trieste, Italy) and collaborators from Japan, Italy, and the US reports novel spectroscopic evidence of a strongly aspherical type Ic supernova.² That's important because a scenario in which a supernova sprouts narrow jets energetic enough to generate a GRB implies that the overall distribution of the supernova's ejected material must be decidedly flattened, presumably by high spin.¹ If most of the ejecta forms a torus in the equatorial plane defined by the spin, the underdense region in the doughnut's hole provides a collimating escape

route. Material energized by falling toward the central black hole can emerge from the hole as polar jets without losing too much energy in plowing through the ejecta. The absence of H and He envelopes in the Ic case makes the escape that much easier. Detailed collapsar-model estimates yield an opening angle of order 5° for the resulting GRB.

No GRB was recorded in conjunction with SN2003jd, the particularly energetic October 2003 supernova examined by Mazzali and company. But the flattening implied by its spectrum suggests that SN2003jd might in fact have created a GRB whose gamma rays were not beamed in our direction.

Model simulation of a strongly aspherical type Ic supernova. Orange and green shadings indicate oxygen and iron concentrations, and contour lines show overall density. The simulated explosion yields shapes for the 6300-Å oxygen emission line (red spectral curves in the two panels) that depend on sight line. A polar observer (top) would see a single unshifted peak (after subtracting the supernova's Hubble redshift). But an equatorial observer (right) would see a red- and blueshifted pair of peaks due, respectively, to the far and near sides of the rapidly expanding, oxygen-rich equatorial torus. If the explosion generated a gamma-ray burst, it would propagate in a narrow polar beam. The black spectral curves in the graphs are measured oxygen lines from two recent type Ic supernovae: SN1998bw did spawn an observed GRB. The double peak from SN2003jd implies that its sight line was approximately equatorial. So if 2003jd did generate a GRB, it would not have propagated in our direction. (Adapted from ref. 2.)



That's called an off-axis GRB. The narrow beaming of GRBs implies that less than one in a hundred can be seen from Earth. So it's difficult to ascertain what fraction, presumably small, of type Ic supernovae actually become GRBs—irrespective of beaming direction.

In the so-called nebular phase of a core-collapse supernova, about a year after the explosion, the remnant is no longer optically thick. At that stage, a strongly flattened expanding torus of ejecta might manifest itself to an observer fortuitously looking edge-on as a telltale pair of Doppler-separated peaks. But such a feature had never been seen in a type Ic spectrum. It's what Mazzali and collaborators were hoping for when they recorded the spectral shape of the nebular 6300-Å emission line of neutral oxygen from SN2003jd, some 250 million light-years away.

An edge-on view would show the emission from oxygen on the near side of the torus blueshifted because it is expanding toward the observer. And the emission from the receding far side of the torus would be redshifted. One must, of course, subtract the overall Hubble redshift due to the distant supernova's recession in the expanding cosmos.

But would this Doppler separation be pronounced enough to discern? That depends on the expansion velocity and shape of the torus as well as on the unknown viewing angle. The figure shows a model simulation of a strongly flattened type Ic explosion. The calculated red curves in the top and right-hand panels show the resulting oxygen line shape that would be seen by an observer with, respectively, a polar or equatorial line of sight. For the equatorial view, the model produces a clear two-horned oxygen line.³ And so does the measurement (black curve, right-hand panel) by Mazzali and company. The group concludes that its line of sight was within about 20° of the flattened supernova's equatorial plane.

The measurement of the SN2003jd oxygen line is in fact a composite of two independent measurements within the collaboration. Ken'ichi Nomoto (University of Tokyo) and other members of the collaboration's Japanese contingent found the two-horned emission line with the 8.2-meter Subaru telescope on Hawaii's Mauna Kea 11 months after the supernova explosion. A month later, the discovery was confirmed with the 10-meter Keck telescope next door by Alex Filippenko (University of California, Berkeley) and coworkers from the US contingent. Filippenko and

colleagues at Lick Observatory in California had originally discovered SN2003jd as part of a robotic supernova search with a much smaller automatic-imaging telescope.

What might polar observers of SN2003jd see? First of all, they would see its GRB, if there was one. With regard to the oxygen line shape in the supernova's nebular phase, the single peak of the calculated red curve in the top panel shows no Doppler shift. That's because the model predicts that the oxygen in the nebula is concentrated near the equatorial plane, which is expanding normal to the polar line of sight.

The predicted oxygen line shape for a polar observer agrees quite well with that measured (the black curve in the top panel) for a historic 1998 type Ic supernova, SN1998bw was the first well-measured supernova clearly associated with a GRB, recorded on 25 April 1998. The good agreement of the flattened type-Ic model with spectroscopic observations from both supernovae makes it tempting to believe that SN2003jd also produced a GRB. But how can we know, given our equatorial line of sight?

Complementary approaches

Finding out what spectroscopic features reliably indicate off-axis GRBs requires help from other observing modes. Classic GRBs are generally followed by radio afterglow. At first, the radio beam is narrowly collimated in the same direction as the gamma beam. But after a week or so of plowing through ambient material, the relativistic jet of ejecta that generated the GRB has slowed enough that its synchrotron radio emission becomes increasingly isotropic.

Alicia Soderberg and coworkers at Caltech have been searching for such late, wide-angle radio emission in the aftermaths of type Ic supernovae in the hope of finding evidence of off-axis GRBs and elucidating the GRB-supernova connection. Looking at SN2003jd nine days after it exploded, they found no telltale radio signal.⁴ Mazzali and company argue² that the limited sensitivity of the initial radio search makes the null result inconclusive. It may just be, suggests Nomoto, that the supernova did create a GRB but the progenitor's rate of mass loss was rather low.

However, longer-term surveillance of SN2003jd by Soderberg and company, reported after the Mazzali paper appeared, still show no evidence of radio afterglow.⁵ Their broader radio survey leads them to conclude that no more than 2% of type

Ic's are associated with off-axis GRBs of typical character.

Several groups are taking yet another observational approach to the intriguing connection between supernovae and GRBs. They seek to determine the asphericities of individual supernovae by measuring the polarization of line and continuum emission from the supernova photospheres in the early, optically thick phase. Craig Wheeler leads such an effort at the University of Texas.⁶ "We're finding that most core-collapse supernovae are substantially aspherical," he says. "Apparently," responds Woosley, "it takes much more than simple asymmetry for type Ic supernovae to make the relativistic jets that GRBs require."

Finding out, in detail, what it does take to generate a GRB will require continued radio and optical surveillance of candidate supernovae for which no GRB is seen. And for GRBs that are beamed our way, the ability of NASA's recently launched *Swift* satellite to localize GRBs faster and more precisely than ever before raises the hope of soon finding a GRB-supernova event near enough to clarify the bond between these two sorts of celestial spectacle.

Bertram Schwarzschild

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