A Supernova Riddle

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Analysis of the polarization of light from supernovae can reveal the shape and distribution of matter ejected from exploding stars. In this “Perspectives” commentary (published: 2007, Science, 315, 193), we review the young field of Type Ia supernova spectropolarimetry and critically evaluate the recent work of Wang et al. (2007, Science, 315, 212), in which a suggestive trend is found in data from 17 Type Ia events.

Roughly once per second in the observable universe, a star explodes and announces its death with an optical display that for weeks rivals the brilliance of its parent galaxy. These supernova events are classified into several types, but among the most interesting are those called type Ia supernovae (SNe Ia). Astronomers’ love affair with these beacons began in earnest about a decade ago when two groups put them to work as distance indicators and precisely mapped the expansion history of the universe well into the regime that gravity was expected to have imprinted its decelerating signature. Instead, the data revealed a universe presently accelerating in its expansion rate, a finding heralded by Science as the “Scientific Breakthrough of the Year” in 1998 (1), and one that has since survived intense scrutiny and complementary experimental checks. Yet for all the fanfare and empirical success, it must be acknowledged that we are fundamentally ignorant: We do not know how these stars explode. On page 212 of this issue, Wang et al. (2) identify a suggestive trend in an impressive set of SN Ia data that may point the
way towards a deeper understanding of these enigmatic cosmic blasts.

Despite an embarrassing dearth of direct observational evidence, the first part of the story of SNe Ia is largely considered settled. Each future SN Ia begins as a carbon-oxygen white dwarf – the compact corpse of a low-mass star like our Sun after its nuclear-burning life is over – accreting matter through some mechanism (mass flow from the envelope of a close companion star seems most likely) until a critical central density is achieved and a thermonuclear runaway is triggered. There is general agreement that, once initiated, the burning front progresses through the star for a time as a subsonic deflagration. But at this point in the story, harmony ends and pitched battles begin, with some favoring an enduring deflagration front and others insisting on a transition to a supersonic detonation.

The most recent “delayed detonation” models appear to better match observed SNe Ia: The events produced in these simulations are bright enough (a perennial problem for deflagration models) and have the proper ejecta composition and stratification (3). The mechanism that triggers the deflagration-detonation transition remains a mystery, however, and so the pure deflagration model still retains its share of adherents. In any event, a complete comparison of the observable distinctions predicted by the two scenarios still awaits full, three-dimensional radiation transport simulations carried out at high enough resolution to resolve physical processes at very small scales. Into this fray, Wang et al. now step, armed with an upstart and potentially powerful observational tool: The ability to study the geometry of the supernova ejecta by analyzing the polarization properties of the light coming from the star shortly after explosion.

Are supernovae round? Simple to pose, this question belies a menacing observational challenge, given that all extragalactic supernovae remain point-like in the night sky throughout the critical early phases of their evolution. Fortunately, geometric information is encoded in the polarization properties of supernova light. The essential idea is that photons become polarized when they scatter off of free electrons, and hot, young supernova atmospheres contain an abundance of free electrons. Indeed, if we could view such an atmosphere as an extended source, rather than as an unresolvable point of light, we would expect to measure changes in both the direction and strength of the polarization as a function of position in the atmosphere. For a spherical, unresolved source, the directional polarization components cancel exactly and yield zero net polarization. Any deviation from perfect symmetry or roundness of the source in the
plane of the sky, however, gives rise to a net polarization (see the figure).

There are two basic causes of supernova polarization. One is asphericity of the electron-scattering atmosphere; because electron scattering is independent of wavelength, it generally produces a uniform increase in the overall polarization level across the spectrum. In the other mechanism, asymmetry in the distribution of material ("clumpy ejecta") above the electron-scattering photosphere unevenly screens the underlying light. Unlike global asphericity, this polarization mechanism is strongly dependent on wavelength, because only those spectral regions corresponding to line transitions of the chemical elements that make up optically thick clumps will be polarized.

From spectropolarimetry gathered on seven events, previous work in this young field has found SNe Ia to have low overall polarizations but occasionally strong line polarization features (4 — 7). The emerging picture is thus one of a globally spherical photosphere with clumpy (or otherwise asymmetrically distributed) ejecta overlying it. How can such studies shed light on the Type Ia flame-propagation mystery? The latest models indicate that pure deflagrations leave behind lumpier ejecta than delayed detonations do (3, 8).

Spotting trends in SNe Ia data has a long tradition of bearing rich fruit. In 1936, Walter Baade pointed out that the substantial homogeneity and extraordinary brightness of these objects could make them powerful cosmological tools. By the early 1990s, however, it became clear that the dispersion in peak intrinsic luminosity (by more than a factor of ten), complicated their use as "standard candles". The fix came in 1993, when Phillips (9) quantified a trend first noticed by Pskovskii (10) that intrinsically bright SNe Ia rise and decline in brightness more slowly than dim ones do. Various versions of the "light curve-width" relation have since provided the edifice upon which the entire SN Ia cosmology enterprise has been built, and served as touchstones for theoretical models of the explosions.

It is just such a trend that Wang et al. now identify in spectropolarimetry of 17 SNe Ia: Bright events show systematically weaker line polarization than dim ones do. This trend is consistent with the idea that different SNe Ia make the transition from deflagration to detonation at different times. The sooner it happens, the brighter the supernova and the more completely scoured the ejecta will be of the clumps left behind by the deflagration front. The agreement between model predictions and observations strengthens the case for a detonation phase.
Will all debate now end on the subject? It is doubtful. Critics will point out that the trend identified by Wang et al. specifically excludes all spectroscopically “peculiar” SNe Ia, which may comprise upwards of 30% of the total population (II). Fundamental advances often come from consideration of the differences seen in a sample, rather than from the similarities alone. And some are likely to withhold any judgment until full three-dimensional models capable of resolving the clumps and quantitatively tracking the resulting polarization become available. Simply put, too many mysteries still surround SNe Ia for anyone to grow complacent. An important clue appears to have been wrested from nature, but we are not ready to resolve the riddle of SNe Ia just yet.

References and Notes

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Producing supernova polarization. A spherical, unresolved supernova atmosphere produces zero net polarization (left), whereas a non-spherical atmosphere does not (center). Clumps of material that unevenly block the photosphere’s light can also produce a net supernova polarization (right), and it is this mechanism that is thought to be responsible for the majority of the observed polarization of SNe Ia.