Science News Online

Week of July 8, 2006; Vol. 170, No. 2

Astronomy Gets Polarized

New angles on exploding stars and the cosmos' first light

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Studying the cosmos by examining polarized light, an endeavor once considered astronomy's stepchild, is now elucidating the shape of supernovas and providing details about the early universe. Some new work focuses on a nearby, recently exploded star, supernova 2004dj, shown at lower left in this Hubble Space Telescope image. (A.V. Fillipenko, P. Challis, et al., NASA, ESA)

Astronomers usually count themselves lucky if a telescope collects enough light to image a distant star or galaxy. But some researchers are getting pickier. No longer content with the average light wave, they don the astronomical equivalent of polarizing sunglasses to eschew all but the tiny fraction of light waves that are polarized.

Groups of light waves are called polarized when their electric fields oscillate in just one direction instead of in random patterns. The phenomenon occurs when light scatters off a clump of charged particles, such as electrons. The intensity and distribution of the polarized light therefore provide information about the environment from which the light has emanated.

But with the meager number of aligned photons coming from most sky objects, "polarization studies used to be the stepchild of astronomy," notes theorist Adam Burrows of the University of Arizona in Tucson. However, high-powered telescopes put in use over the past decade can collect even small amounts of polarized light.

Polarization is giving new insight into the death throes of stars, some of the most spectacular fireworks in the universe. These explosions, known as supernovas, have a profound influence on the cosmos. They supply the heavens with most of the elements heavier than helium and hurl shock waves that can trigger the birth of new generations of stars.

Yet researchers don't know the full story of how stars blow up. The bright light radiated by the outermost layers of blast debris obscures the inner parts of a supernova. But as the outer debris layers thin and become more transparent, polarization studies can detect new details of the supernova mechanism.

Probing an era well before the first supernova explosions, astronomers have begun measuring the polarization of the first light in the universe—the radiation left over from the Big Bang. These measurements are describing the earliest moments of the cosmos as well as pinpointing the time when the first stars began to glow.

Behind the lens

To understand how a polarizing filter, or spectropolarimeter, works, picture a star like Betelgeuse that's bright enough to be seen with the naked eye. Consider what will happen when Betelgeuse goes supernova, as astronomers expect it to do within the next million years.

To make a crude estimate of light's polarization from such a nearby explosion, a pair of polarized sunglasses would be sufficient, says Doug Leonard of San Diego State University. A person would just have to look at the burst through the sunglass lens while slowly rotating it 180°. The lens orientation at which the exploded star appeared brightest and the intensity of light there would provide the same sort of information that astronomers obtain from a spectropolarimeter.

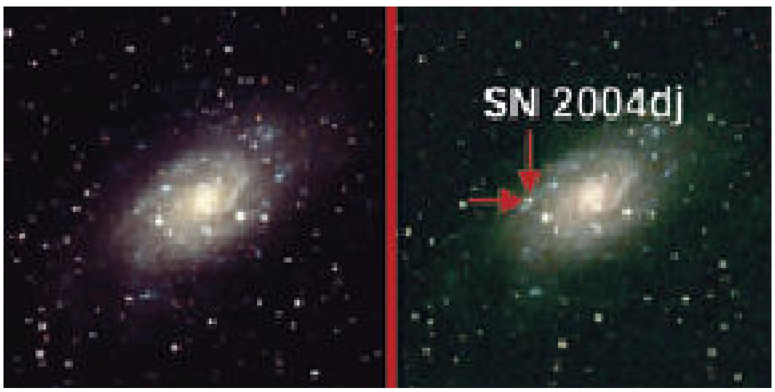
If the Betelgeuse supernova appeared equally bright no matter the angle of the sunglass lens, then it would be radiating the same amount of light at all angles, as a perfectly round ball of gas does. But if the light from the Betelgeuse supernova appeared brighter at certain angles, then it must be asymmetric, perhaps egg-shaped. The greater the polarization, the more out of round the supernova would be.

Sunglasses work by preventing half the polarized light—the glare from the ocean, for example, from passing through the lenses. But a modern spectropolarimeter preserves all the light, incorporating a beam splitter so that both a polarized beam and the beams at right angles to it are recorded simultaneously.

“One does not see deeper into an object using polarimetry,” says Leonard, “but rather, astronomers are better able to interpret the light coming from an astronomical source by knowing its polarization state.”

Because even the largest telescopes can’t discern the shapes of the explosions, astronomers turn to polarization to find subtle indications of geometry.

Astronomers divide supernovas into two general types. The most common, known as core-collapse supernovas, are the catastrophic deaths of massive, bloated stars. The cores of these heavyweights implode under their own weight, creating either a neutron star or a black hole and blasting their outer layers into space.



SCENE CHANGE. A galaxy before (left) and after (right) the violent demise of a star in an explosion known as supernova 2004dj. (K. Sarneczky, Leonard)

The less-massive supernovas, which are called type 1a, explode in a different manner. Astronomers’ current view is that an elderly, shriveled star, called a white dwarf, siphons mass from a companion star until the dwarf reaches a critical mass about 1.4 times as great as that of our sun. The weight of the infalling material triggers a thermonuclear explosion on the dwarf’s surface, demolishing the star.

Astronomers are using polarization to examine both types of supernovas. The work has already revealed a surprise. Although core-collapse supernovas arise from symmetrical objects and type 1a explosions come from naturally asymmetric configurations, the core-collapse supernovas appear to be more mis-shapen.

Polar opposites

Until recently, even spectropolarimeter readings failed to discern the shapes of supernovas. That’s because researchers could read the polarized light only from the hydrogen envelope of the explosions, not from the inner layers.

Astronomers had one important clue that the average core-collapse supernova might be out of round. Observations of neutron stars, the cinders left behind by many of these explosions, indicate that they go flying off in a specific direction with velocities of several hundred kilometers per second. The most plausible explanation for such a kick is that the explosion was much stronger in that direction. But researchers lacked compelling proof.

Over the past few years, astronomers have measured the polarization of a few, rare core-collapse supernovas that arose from stars in which strong winds had blown away the puffy envelopes of hydrogen that surround most stars. Some of these stripped-down supernovas are associated with gamma-ray bursts, which theorists hypothesize are produced by jets of ionized particles emerging from the exploding stars. The emergence of the jets is an indication that these supernovas are more powerful in some directions than others.

Polarization measurements by Lifan Wang of the Lawrence Berkeley (Calif.) National Laboratory, Craig Wheeler of the University of Texas at Austin, and their colleagues bear this out. Their data indicate that these supernovas are indeed mis-shapen, with lengths about 1 percent greater than their widths.

But the scientists have wondered whether all core-collapse supernovas are slightly lopsided, or just these few oddballs. The answer, says Wheeler, is vital to understanding how stars explode.

On July 31, 2004, astronomers got a break. That's the day they discovered SN 2004dj, the nearest known core-collapse supernova to pop off in more than a decade. Because SN 2004dj exploded in a galaxy just 10 million light-years away, researchers suspected that polarized light emerging through the hydrogen cloud might be discernible on Earth.

Not only was SN 2004dj nearby, but it belongs to the most common class of core-collapse supernova. So, the shape of this supernova is considered indicative of that of many others.

Leonard and his colleagues began studying the supernova just a few days after it was spotted. The team used spectropolarimeters at two sites in California: the 5-meter Hale Telescope on Palomar Mountain near Escondido and the Lick Observatory's telescope on Mount Hamilton near San Jose. The researchers had to wait for the obscuring envelope of hydrogen to thin and cool, enabling them to see polarized light from deeper layers.

Astronomers predicted that it would take several months for the hydrogen envelope to cool to transparency. Indeed, 3 months after the supernova was first sighted, the observation team recorded an abrupt change in the exploded star.

The light's polarization dramatically increased, indicating that the center of the explosion was much more misshapen than its outer layers. The length of SN 2004dj was about 30 percent greater than its width, Leonard and his colleagues reported in the March 23 Nature.

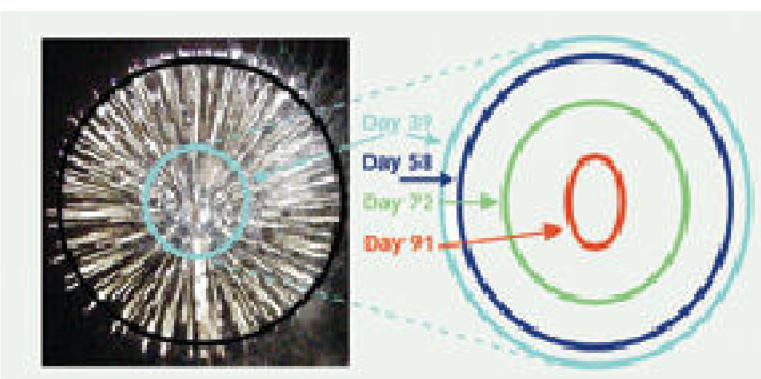
"What Leonard did was to wait patiently and then look very carefully at just the [right] time," says Wheeler. Studies by several teams have now shown "that the polarization gets larger the deeper into the [supernova] ejecta one looks. That has been widely interpreted to mean that it is the machine of core collapse that is asymmetric, not some incidental aspect of the environment."

In 2001, an amateur astronomer spotted an erupting type 1a supernova in a nearby galaxy. Wang and his colleagues, including Wheeler, examined it with a spectropolarimeter that they had just installed on one of the four instruments that make up the Very Large Telescope in Paranal, Chile.

A small amount of polarized light was coming from the explosion, dubbed SN 2001el, but after a week of maximum overall brightness, the polarization dropped to zero. The change revealed to the astronomers that in a process nearly opposite that of the core-collapse-supernovas, the outer layers of the explosion had grown diffuse and revealed non-polarizing inner layers of SN 2001el.

In a type 1a explosion, says Wang, "the outer part is aspherical, but as we see lower down, the dense inner core is spherical."

He adds that the observations of SN 2001el support the prevailing model of how type Ia supernovas burn up.



CORE FINDING. Exploding firework (left) represents supernova 2004dj. As the outermost layers of material blasted into space by the supernova thinned and cooled over a period of about 3 months, polarization studies viewed deeper and deeper layers of the explosion. (Leonard, et al.)

More bang

Examining polarization on a much grander scale, astronomers are scrutinizing the radiation that's left over from the Big Bang and has now cooled to a faint microwave glow. On its epic trip across the universe, this radiation twice encountered clumps of free-floating, polarizing electrons.

The earliest encounter, known as recombination, dates to 400,000 years after the birth of the universe. That encounter occurred just before the cosmos cooled enough for electrons to combine with protons and make hydrogen atoms. The second rendezvous came several hundred million years later, when the first stars illuminated the universe and ionized the gas around them, creating polarizing electrons.

NASA's Wilkinson Microwave Anisotropy Probe, a satellite launched in 2002, has measured the subtle, large-scale polarization resulting from the background radiation's meeting with the first stars. Astronomers analyzing the first 3 years of data from the satellite recently concluded that polarization indicates that no star formed until 400 million years after the Big Bang (SN: 3/18/06, p 163: http://www.sciencenews.org/articles/20060318/fob1.asp). That's about 200 million years later than preliminary data from the satellite had indicated, and more in line with theoretical predictions of the birth of the first stars.

Measuring the polarization signal from the universe's first stars has a second payoff. Researchers recently used the data to confirm inflation, a key part of the Big Bang story line. Inflation posits that the universe underwent a tremendous growth spurt at its start, expanding by a factor of 1026 in a tiny fraction of a second. According to the theory, this rapid expansion greatly amplified chance, subatomic fluctuations in the density of the otherwise perfectly uniform cosmos. Those amplified fluctuations then became the seeds from which all the clumpy structure of the universe—stars and galaxies—arose.

The primordial fluctuations—what astronomers call the cosmic seeds—are imprinted in the microwave background as variations in temperature that, although tiny, are about 100 times as large as those created by polarization. By measuring and subtracting the effect of polarization on the microwave background, cosmologists will have more-accurate measures of the temperature variations that are a direct consequence of inflation.

The simplest version of inflation dictates that the microwave background have slightly larger variations in temperature over larger patches of sky than smaller patches. With the polarization signal removed, that's just what scientists are finding, says cosmologist David Spergel of Princeton University.

"This is a significant milestone in cosmology," he adds.

Polarization is astronomy's stepchild no longer.

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Further Readings:

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For more information on polarization and type 1a supernovas, go to http://www.lbl.gov/Science-Articles/Archive/SB-Phy-supernovae-shapes-1.html.

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From Science News, Vol. 170, No. 2, July 8, 2006, p. 24.