Supernova Polarimetry with the VLT: Lessons from Asymmetry

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1. Introduction

Picture a 55-year-old telescope of modest two-metre aperture and the need to take multiple spectral exposures of the same object to elicit any signal from the noise with an inexpensive spectrograph jury rigged to do polarimetry, an effort requiring integrations on a single object lasting a whole long winter night with a single observer and no night assistant, if any transient target is available during the scheduled time. Contrast that with ordering up queue-scheduled target-of-opportunity observations by a dedicated professional staff on an 8 metre telescope with a state-of-the-art spectrograph and polarimeter. That is the leap that has occurred in our programme to obtain spectropolarimetry of all accessible supernovae. The spectropolarimetry obtained in a brief exposure on the VLT with the FORS1 spectrograph is comparable to the total flux spectrum obtained on those long nights on the 2.1-m Struve Telescope at McDonald Observatory where this programme began. While the data obtained at McDonald pointed the way to a revolution in the way we think about supernovae, it is the quality of the data from the VLT that has led the programme to flourish.

Supernovae have been studied with modern scientific methods for nearly a century. During this time, it has been traditional to assume that these catastrophic stellar explosions are, for all practical purposes, spherically symmetric. There were observational reasons for this. The Sun is essentially spherically symmetric and most stars are thought to be. The assumption that stars are round is quite reasonable. Self-gravity will tend to pull any large body into a sphere which is the minimum-energy configuration. There were also practical reasons. Theoretical study of stellar explosions has been difficult enough even with the assumption of spherical symmetry. There has been no commanding observational need to abandon that simplifying assumption. Now there is.

The evidence that supernovae may depart a little or even drastically from spherical symmetry has been growing for years. Neutron stars were predicted to form and to power supernovae by Fritz Zwicky shortly after the discovery of the neutron in 1932. When the first neutron stars were discovered by Jocelyn Bell they were manifested as rapidly rotating pulsars with intense magnetic fields. Pulsars have space velocities that average several hundred kilometres per second. This indicates that they are somehow “kicked” at birth in a manner that requires a departure from both spherical and up/down symmetry. More recently, NTT and then Hubble Space Telescope images of Supernova 1987A in the Large Magellanic Cloud showed rings of gas that had been ejected by the progenitor star before it exploded. This means either the progenitor star or its surroundings possessed some sort of asymmetry. Further observations showed that the debris of the explosion were also asymmetric. The supernova remnant Cassiopeia A shows signs of a jet and counterjet that have punched holes in the expanding shell of debris and there are numerous other asymmetric supernova remnants. Each of these things has been known. The question has been: are they merely incidental or a vital clue to how supernovae work?

The previous discussion pertained to core-collapse supernovae. These come in a variety of spectral classifications, Type II, Type Ib or Type Ic, depending on whether there is abundant hydrogen, helium or neither in the outer layers. There is another kind of supernova known as Type Ia. These are thought to be the result of the thermonuclear explosion of a white-dwarf star composed of carbon and oxygen. When the mass of the white dwarf closely approaches the Chandrasekhar limit of about 1.4 solar masses, the carbon ignites. The resulting thermonuclear explosion is thought to completely disrupt the star, leaving no compact remnant. This sort of explosion has received prominence recently because they have been the tool to discover the accelerating Universe and the dark energy that drives the expansion. The progenitor white dwarf has long been treated as basically spherically symmetric even though the popular model is that the explosion must take place in a binary system where the white dwarf grows to the critical mass by accretion of mass and, inevitably, angular momentum. There could be asymmetries in this sort of supernova resulting from the spin of the white dwarf, the motion of the orbit, a surrounding accretion disk, or the presence of the companion star. As for the case of core-collapse supernovae, this was known, but there was no compelling observational reason to consider departures from spherical symmetry. This, too, is changing.

2. Polarization of Supernovae

The question of the shape of supernovae has undergone a revolution in the last decade. The driving force has been a new type of observation: measurement of the polarization of the light from supernovae.

Light consists of oscillating electric and magnetic fields. An ordinary beam of light is a mix of photons with all orientations equally present, a state that leaves the light unpolarized on average. Some processes of producing or scattering light favour certain orientations of the electric and magnetic fields over others. One such process is the reflection of light. When light scatters through the expanding debris of a supernova, it retains information about the orientation of the scattering layers. If the supernova is spherically symmetric, all orientations will be present equally and will average out, so there will be no net polarization. If, however, the gas shell is not round, a slight net polarization will be imprinted on the light.

Since we cannot spatially resolve the average extragalactic supernova, polarization is the most powerful tool we have to judge the shape of the ejecta. The method used is called spectropolarimetry. This technique both spreads the light out into its spectrum of colours and determines the net orientation of the electric field at each wavelength. This way both the overall shape of the emitting region and the shape of regions composed of particular chemical elements can be determined. We note that the effective spatial resolution attained by polarimetry of a supernova of radius 10^{15} cm at 10 Mpc is 10 microarcsec. This is a factor of 100 better resolution than VLTI or other comparable optical interferometer installations – and at a tiny fraction of the cost.

There were systematic and stimulating observations of the polarization of the light of SN 1987A that are still being studied and interpreted. Another event that was modestly well studied was the hydrogen-depleted event SN 1993J in M81. These two events just illustrated how poor the overall data base of supernova spectropolarimetry was. In 1994 we began a programme to obtain spectropolarimetry of as many supernovae as possible that were visible from McDonald Observatory. At the time, only a handful of events had been examined at all and there were virtually no statistics. The data reduction was tricky, if only because the intervening interstellar medium can impose a polarization signal that has nothing to do with the supernova.

The data were also difficult to interpret. There are, in principle, many reasons why the light from a supernova could be polarized. The supernova could be aspherical, it could be spherical but have off-centre sources of light, or other matter in the vicinity could be asymmetrically distributed, blocking part of the scattering surface and yielding a net polarization signal from even a spherical surface. To make matters worse, the first few supernovae our group studied (and those in the previous sparse record like SN 1987A and SN 1993J) were classified as "peculiar" in some way, so we did not know whether we were seeing incidental peculiarities or something truly significant.

As data accumulated, however, this uncertainty was removed, and significant new insights were revealed. With more data and better statistics, we identified the first key trend. In 1996, we realized that the data were bi-modal. Type Ia supernovae showed little or no polarization signal (we will talk about some significant exceptions below). Supernovae thought to arise by core collapse in massive stars – Types II, Ib, and Ic – were, by contrast, all significantly polarized. So far there has been no exception. Every core-collapse supernova for which we or other groups have obtained adequate data has been substantially polarized. Core-collapse supernovae are definitely not spherically symmetric. The question is, why? As data continued to mount, new trends appeared that give critical clues to address that question.

Normal Type II supernovae explode in red-giant stars that retain large, massive outer envelopes of hydrogen. Types Ib and Ic are thought to happen in stars that have already shed much or all of their outer hydrogen layers, so they allow us to see deeper into the heart of the exploding star. We noticed that the Type II supernovae, with their large blankets of hydrogen, showed relatively less polarization. The Type Ib and Ic that allowed us to peer deeper into the exploding matter had higher polarization. In addition, as a given supernova expands, the debris thins out and allows us a view deeper inside. We found that even in a Type II supernova, the longer we watched and the deeper inside we could see, the larger the polarization became. This was illustrated by our VLT observations of the classic Type II supernova, SN 1999em, that was characterized by an especially long plateau, suggesting an especially massive outer hydrogen envelope. Observations were obtained around optical maximum and about 2 months past optical maximum. The polarization rose from 0.1 per cent in the early observations to about 1 per cent in the later data. Figure 1 shows the data for SN 1999em on a "Q-U" plot where Q and U represent different projections of the polarization vector. The striking feature of the SN 1999em data presented in this way is that all the data points fall on a single line. This suggests a well-defined symmetry axis throughout the ejecta and independent of wavelength. The explosion of SN 1999em is asymmetric, but aligned in a significant way. Figure 2 shows data from another Type II event, SN 2001dh, that also shows this tendency to follow a fixed orientation in space.

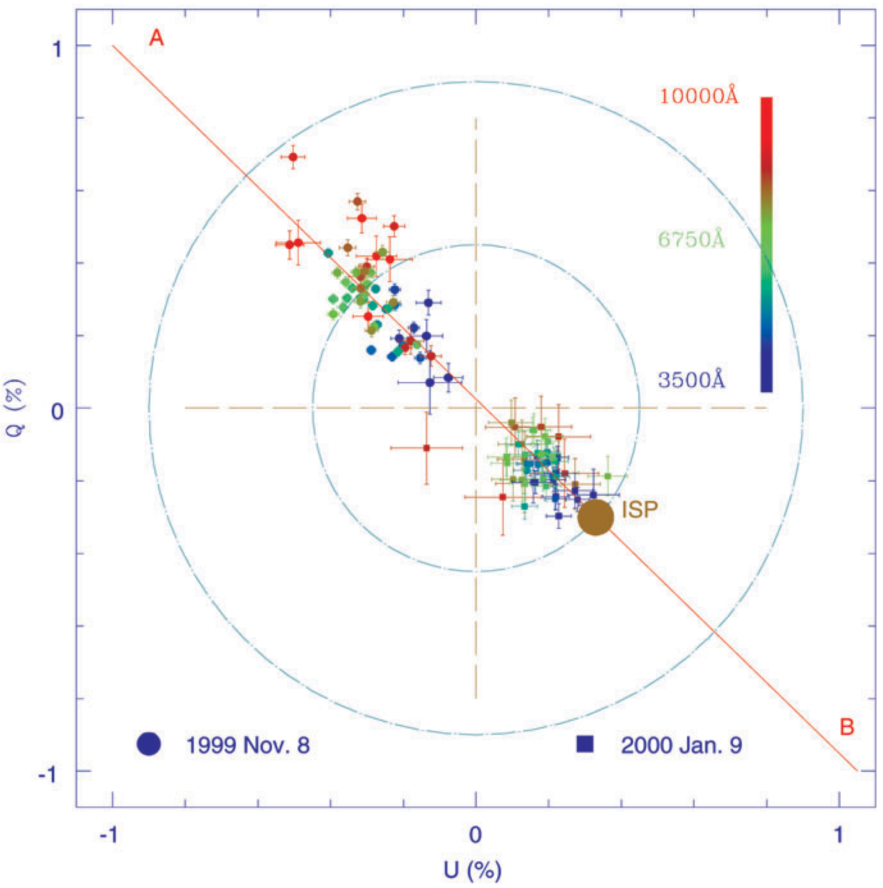

Figure 1: Polarimetry of the Type II SN 1999em on the Q-U plane. The wavelength of different data points are colour encoded. The data points are rebinned to 100 Å for clarity. The 1999 Nov 8 data (clustered in the lower-right quadrant) are clearly separated from the 2000 Jan. 9 data (clustered in the upper-right quadrant), suggesting strong polarization evolution. The data points of both epochs fall roughly on the line denoted AB. Line AB defines the axis of symmetry if the object is axially symmetric. Note that the blue and red dots are well separated for each epoch with the blue points preferentially located at the lower-right of the data cluster of each observations. The circles are the upper limits to the interstellar polarization assuming E(B-V) toward the supernova to be 0.05 (inner circle) and 0.1 (outer circle). The approximate location of the component due to interstellar dust is shown as a solid circle.

These observations of core-collapse supernovae taken together tell us that the closer we see to the centre, the larger is the asymmetry. The asymmetry is not some incidental aspect of the progenitor's surrounding environment that is causing the polarization, but something deep in the heart of the explosion. The implication is that the explosion mechanism itself is asymmetric.

3. The Cause of Asymmetry in Core Collapse

The fact that the asymmetry of many core-collapse supernovae is aligned in one direction provides an important clue to the engine of the explosion. The explosion mechanism must impose some axial symmetry. There must be some sustained bi-polar influence because otherwise, as the supernova expands, pressure gradients will tend to heal irregularities and the ejecta will tend to become more spherical rather

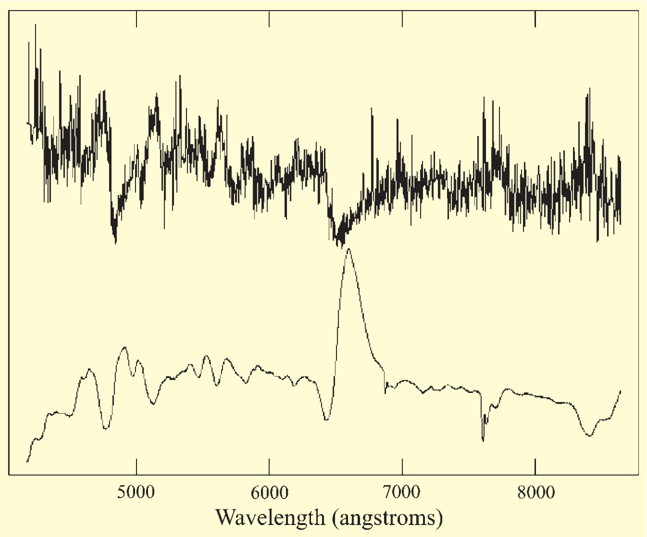

Figure 2: A total flux spectrum (bottom) and polarization spectrum (top) of the Type II SN 2001dh, obtained on August 8, 2001 with the VLT. In the top panel the locations of the prominent lines of hydrogen and other elements can be identified by the emission peaks at these wavelengths. To the short wavelength side of the emission peaks are Doppler blue-shifted absorption troughs corresponding to absorption in the expanding atmosphere of the supernova. The average polarization at the epoch of these data (a week or so after discovery) was about 1 to 2 per cent. The peaks and troughs in the polarization spectrum prove that the polarization comes from the supernova, not the intervening interstellar matter. Some of the features correspond to those in the total flux spectrum, but others correspond to features that are only clearly revealed by the polarization.

than less. To do what we see, the mechanism that drives the supernova must produce energy and momentum asymmetrically from the start, then hold that special orientation long enough for its imprint to be permanently frozen into the expanding matter. Appropriate outflows might be caused by MHD jets, by accretion flow around the central neutron star, by asymmetric neutrino emission, or by some combination of those mechanisms.

The light we see from a supernova comes substantially from the decay of short-lived radioactive elements, nickel-56, cobalt-56 and later titanium-44 in the debris. If this material is ejected in a bi-polar fashion, then the overall debris shell could be nearly spherical, while the asymmetric source of illumination leads to a net polarization. This mechanism may be at work in the early phases of Type II supernovae such as SN 1999em and SN 2001dh.

By injecting jets of mass and energy up and down along a common axis deep within a model of an evolved star, we have shown that typical asymmetric configurations emerge. As shown in Figure 3, bow shocks form at the heads of the jets as they plow through the core, and a significant portion of the star's matter bursts through the core along the jet axis. The bow shocks also drive "transverse" shocks sideways through the star. These shocks proceed away from the axis, converge toward the star's equator, and collide in the equatorial plane. From there, matter is compressed and ejected in an equatorial torus perpendicular to the jets. These models have shown that sufficiently energetic jets can both cause the explosion and imprint the observed asymmetries. Whether this process can alone explain the explosion or whether it merely supplements the standard neutrino-driven explosion remains to be seen. If the jets up and down the symmetry axes are somewhat unequal, they might also account for the runaway velocities of pulsars.

If such jets produce the asymmetries, the most likely cause of the jets are the fast rotation and magnetic fields that are intrinsic to pulsars. Progress in understanding the origin of jets from magnetized disks around black holes makes us optimistic that similar processes will form jets from a newborn pulsar in a stellar core. Recent work in Austin has shown that the magnetorotational instability may play a significant role to produce strong magnetic fields in a fraction of a second after core bounce. These fields may, in turn, promote the flow of energy up the rotation axis by a combination of hoop stresses and other pressure anisotropies.

4. SN 2002ap – Not a Hypernova?

This work may also shed light on the supernova/gamma-ray burst connection. Several supernovae have been identified as "hypernovae" since they show excessive velocities and luminosity. The most famous example, SN 1998bw, was apparently associated with the gamma-ray burst of April 25, 1998. We have been concerned that asymmetric explosions could mimic some of the effects of "hypernova" activity as interpreted by spherical models. In particular, asymmetric models could give especially high velocities in some directions, the directions of axial jets, and be brighter in some directions than others because of the resulting asymmetric flux distribution. This could

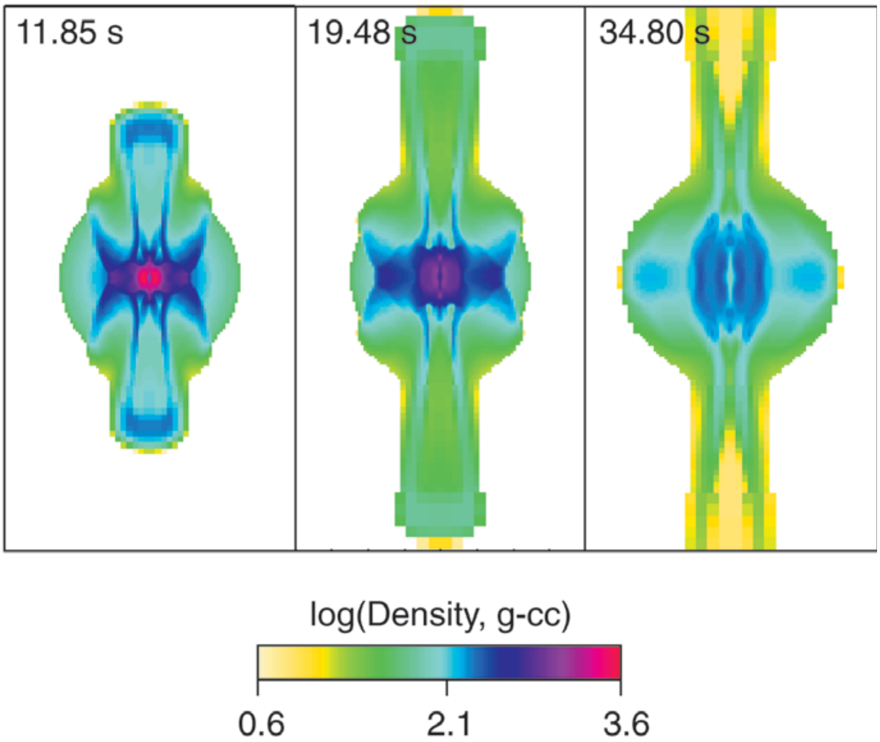

Figure 3: Three-dimensional computation of a jet-induced supernova explosion in a helium core. The frames show the density in the plane parallel to the jet axis that passes through the centre of computational domain. The time since the beginning of the simulation is given in the upper left corner of each frame. The scale expands in each frame with the left frame being about 10^{10} cm, the middle frame about 5×10^{10} cm and the right frame about 10^{11} cm. Note the transverse shock waves that converge on the equator. From Khokhlov et al. 1999, Astrophys. J., 524, L107.

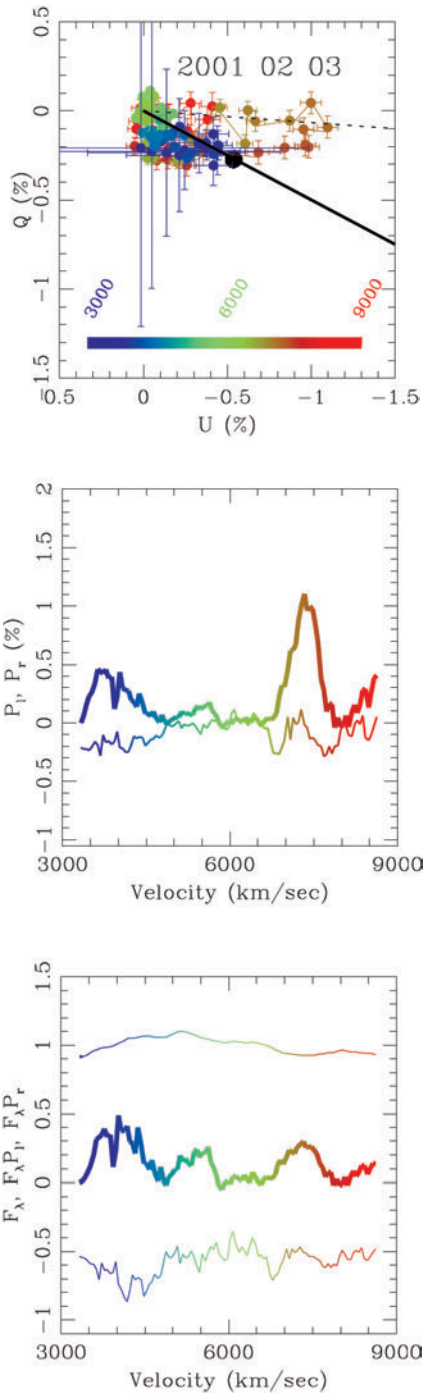

Figure 4: Spectropolarimetry of the Type Ic SN 2002ap on 2002 3 Feb, 6 days before V maximum. The Stokes parameters Q and U are rebinned into 15 Å bins. An interstellar polarization component is subtracted from the observed Stokes parameters so that the data points represent intrinsic polarization due to the supernova. The assumed interstellar polarization is shown as the solid dot in the Q–U plot (top panel). Without subtraction of the interstellar component, the origin of the coordinates would be centred at this solid dot. The solid line represents the axis from the origin through the value of the ISP. The dashed line illustrates the locus of the O I feature in the Q–U plot. The polarization spectra (middle panel) and polarized flux (bottom panel) show conspicuously polarized spectral features corresponding to Fe II, Na I D, and O I 777.4 nm. The wavelength colour code is presented at the bottom of the top panel.

be especially true for Type Ic events where the lack of hydrogen and helium envelopes give a close view of the asymmetries of the inner explosion.

A particular case in point is the recent Type Ic event SN 2002ap. This event showed high velocities, but none of the other characteristics of a “hypernova,” neither a strong relativistic radio source, nor excessive brightness. High-quality spectropolarimetric data of SN 2002ap were obtained with the VLT Melipal and the FORS1 spectrograph at 3 epochs that correspond to –6, –2, and +1 days for a V maximum of 9 Feb 2002. A sample of the data is presented in Figure 4. The polarization spectra show three distinct broad (~ 100 nm) features at ~ 400, 550, and 750 nm that evolve in shape, amplitude and orientation in the Q-U plane. The continuum polarization grows from nearly zero to ~ 0.2 per cent. The 750 nm feature is polarized at a level $\gtrsim$ 1 per cent. We identify the 550 and 750 nm features as Na I D and OI λ 777.4 moving at about 20,000 km s^{-1}. The blue feature may be Fe II.

We interpret the polarization evolution in terms of the impact of a bi-polar flow from the core that is stopped within the outer envelope of a carbon/oxygen core. Although the symmetry axis remains fixed, as the photosphere retreats by different amounts in different directions due to the asymmetric velocity flow and density distribution, geometrical blocking effects in deeper, Ca-rich layers can lead to a different dominant axis in the Q-U plane. The features that characterize SN 2002ap, specifically its high velocity, can be accounted for in an asymmetric model with a larger ejecta mass than the well-studied Type Ic SN 1994I such that the photosphere remains longer in higher velocity material.

We conclude that the characteristics of “hypernovae” may be the result of orientation effects in a mildly inhomogeneous set of progenitors, rather than requiring an excessive total energy or luminosity. In the analysis of asymmetric events with spherically symmetric models, it is probably advisable to refer to “isotropic equivalent” energy, luminosity, ejected mass, and nickel mass.

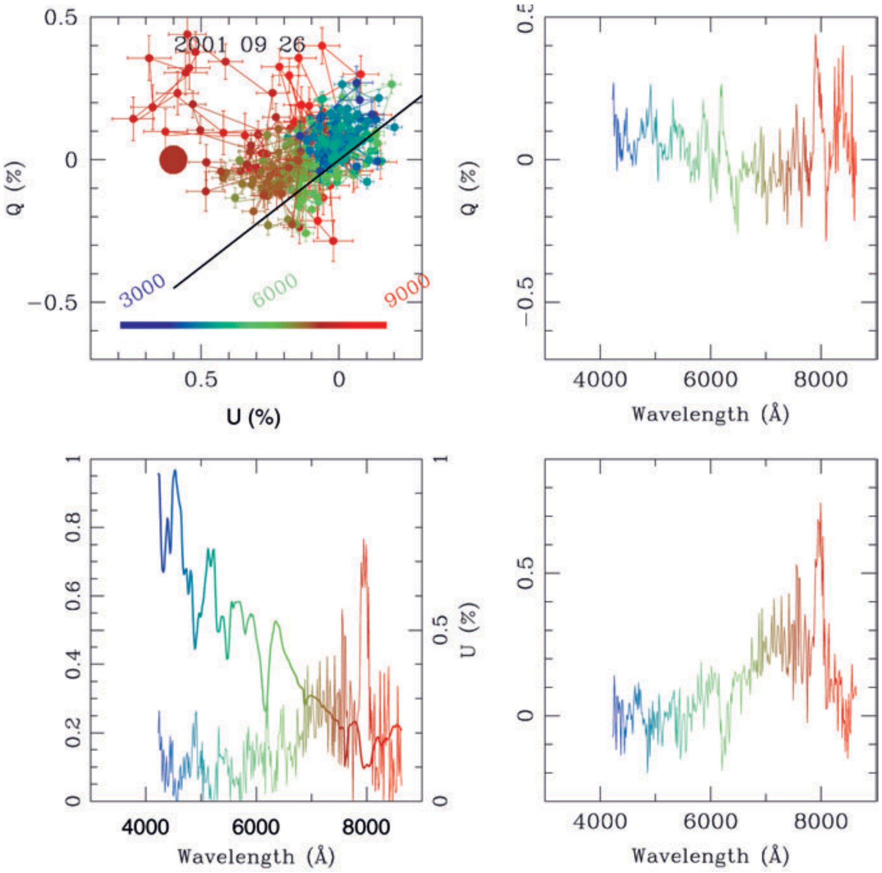

Figure 5: Spectropolarimetry of the Type Ia SN 2001el on 2001 Sept. 26, 7 days before maximum. The Stokes parameters Q and U are rebinned into 15 Å bins. An interstellar polarization component is subtracted from the observed Stokes parameters so that the data points represent intrinsic polarization due to the supernova. The assumed interstellar polarization is shown as a solid dot in the Q–U plot (panel a, upper left). Without subtraction of the interstellar component, the origin of the coordinates would be centred at this solid dot. The straight line illustrates the dominant axis shifted to the origin of the Q–U plot. The Q (panel b, upper right) and U (panel d, lower right) spectra show conspicuously polarized spectral features. The degree of polarization is shown as the thin line in panel c (lower left) with the flux spectrum (panel c, lower left, thick line) overplotted to show the correlations of the degree of polarization and the spectral features. The wavelength colour code is presented at the bottom of panel a.

5. Asymmetries in Type Ia Supernovae

Most Type Ia supernovae are not substantially polarized at the epochs that have been observed. This suggests that, despite occurring in binary systems, the explosions are essentially spherically symmetric. There are some interesting exceptions to this, however. SN 1999by was one of the class of subluminous, rapidly declining Type Ia events. It was substantially polarized and hence asymmetric in some way. We do not yet know whether this was characteristic of subluminous Type Ia, or whether SN 1999by was odd in this regard.

In this context, it is important to obtain spectropolarimetry of "normal" Type Ia supernovae. A step in this direction was taken with our observations of the Type Ia SN 2001el. High-quality spectropolarimetry of the SN 2001el was also obtained with VLT Melipal and FORS1 at 5 epochs. Some of these data are shown in Figure 5. The spectra a week before and around maximum indicate photospheric expansion velocities of about 10,000 km s^{-1}. Prior to optical maximum, the linear polarization of the continuum was ≈ 0.2–0.3% with a constant position angle, showing that SN 2001el has a well-defined axis of symmetry. The polarization was nearly undetectable a week after optical maximum.

The spectra of SN 2001el are similar to those of the normally-bright SN 1994D with the exception of a strong double-troughed absorption feature seen around 800 nm (FWHM about 22 nm). The 800 nm feature is probably due to the Ca II IR triplet at very high velocities (20,000–26,000 kms^{-1}). The 800 nm feature is distinct in velocity space from the photospheric Ca II IR triplet and has a significantly higher degree of polarization (= 0.7%), and different polarization angle than the continuum. Taken together, these aspects suggest that this high velocity calcium is a kinematically distinct feature with the matter distributed in a filament, torus, or array of "blobs" almost edge-on to the line of sight. This feature could thus be an important clue to the binary nature of SN Ia, perhaps associated with an accretion disk, or to the nature of the thermonuclear burning, perhaps representing a stream of material ballistically ejected from the site of the deflagration to detonation transition.

If modelled in terms of an oblate spheroid, the continuum polarization implies a minor to major axis ratio of around 0.9 if seen equator-on; this level of asymmetry would produce an absolute luminosity dispersion of about 0.1 mag when viewed at different viewing angles. If typical for SNe Ia, this would create an RMS scatter of several hundredths of a magnitude around the mean brightness-decline relation. This scatter might have implications for the high precision measurements required to determine the cosmological equation of state of the "dark energy."

6. Conclusions

The acquisition of systematic supernova polarization data has led to remarkable new insights. It seems likely that all core-collapse supernovae are substantially asymmetric. They explode by means of bi-polar flow associated with the newborn neutron stars. This discovery may, in turn, give new insights into more exotic jet-induced events like gamma-ray bursts. While most Type Ia supernovae have been found to be little polarized, the number of exceptions is growing. The asymmetries observed in Type Ia may finally yield direct observational evidence that they occur in binary systems, as long assumed, and clues to the combustion mechanism. Understanding these asymmetries may be necessary to properly interpret future data on cosmologically distant Type Ia's.

The authors are grateful to the European Southern Observatory for the generous allocation of observing time. We are also anxious to acknowledge that, contrary to the impression perhaps given in the Introduction, requests for service-mode observations with the VLT are much different than orders to a pizza home-delivery service: The Paranal Science Operations staff and the User Support Group in Garching have gone to considerable effort to augment our proposal with their full range of expertise. We recognize that accommodating our target-of-opportunity observations in an already busy observing and work schedule often poses a special extra challenge. Only this symbiosis enables the ongoing success of this project. We are especially grateful for that. This work was supported in part by NASA Grant NAG5-7937 to PAH and NSF Grant AST 0098644 to JCW.

OTHER ASTRONOMICAL NEWS

An Exciting Working Session on Cataclysmic Variables at ESO/Santiago

E. MASON (ESO/Chile, fellow) and S. HOWELL (ESO/Chile, visiting scientist)

An intensive working session on Cataclysmic Variables (CVs) was held at ESO/Santiago on August 14, 2002. The workshop was organized on the occasion of the presence in Santiago of Dr. S. Howell, from the Planetary Science Institute in Tucson, thanks to the ESO/Chile visiting scientist programme.

The goal of the workshop was to gather all astronomers in Chile working on CVs, for exchanges and fruitful discussions. The participants were from the University of Concepción and from ESO/Chile, and we could also welcome Dr. N. Vogt, from Heidelberg, who had organized the first workshop on CVs ever held in Chile (Viña del Mar, 1992). We hope that the wealth of ideas and projects discussed during the working session, will trigger regular CV workshops here in Chile, possibly involving a larger number of participants and invited speakers. The workshop was organized in a morning review session on CVs, both on observations and on theory, and an afternoon discussion session.

Reviews were about: (i) the photometric behaviour of dwarf novae (DNs) during cycles and super-cycles, (ii) the spectroscopic characteristics of CVs in the wavelength range UV-IR, (iii) the evolution of CVs – theory vs. observations, (iv) radial velocity measurements as a diagnostic for the binary system geometry and (v) the CVs accretion disks and current analysis of their emission lines.

The afternoon talks were more specifically focused on the observation of particular objects or on some aspects of theoretical modelling.

The participants really benefited from being in a fairly small but highly motivated group and could present, discuss, and confront various problems and results of their current research programmes. In particular, the discussion of unsolved problems turned out to be important and fruitful as it triggered the submission of new proposals (on ESO telescopes!), as well as the development of new research projects and collaborations.