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Spectropolarimetry of Type Ibc Supernovae

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Abstract. Studying a multi-dimensional structure of supernovae (SNe) gives important constraints on the mechanism of the SN explosion. Polarization measurement is one of the most powerful methods to study the explosion geometry of extragalactic SNe. Especially, Type Ib/c SNe are the ideal targets because the core of the explosion is bare. We have performed spectropolarimetric observations of Type Ib/c SNe with the Subaru telescope. We detect a rotation of the polarization angle across the line, which is seen as a loop in the $Q-U$ plane. This indicates that axisymmetry is broken in the SN ejecta. Adding our new data to the sample of stripped-envelope SNe with high-quality spectropolarimetric data, five SNe out of six show a loop in the $Q-U$ plane. This implies that the SN explosion commonly has a non-axisymmetric, three-dimensional geometry.

Keywords. supernovae: general, techniques: polarimetric

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1. Introduction

The explosion mechanism of supernovae (SNe) has been unclear for a long time after the first concept by Burbidge *et al.* (1957) and the first numerical simulation by Colgate & White (1966). According to modern numerical simulations, a successful explosion cannot be obtained in one-dimensional simulations. And it is suggested that multi-dimensional effects, such as convection (e.g. Herant *et al.* (1994)) and Standing Accretion Shock Instability (SASI, e.g. Blondin *et al.* (2003)) are important.

Given these circumstances, it is important to obtain observational constraints on the multi-dimensional geometry of SN explosions. Spectropolarimetry is one of the most powerful methods to study the multi-dimensional geometry of extragalactic SNe (see Wang & Wheeler (2008) for a review). To study the explosion geometry with spectropolarimetry, Type Ib/c SNe are the ideal targets because the core of the explosion is bare. We have performed spectropolarimetric observations of Type Ib/c SNe with the Subaru telescope. In these proceedings, we summarize spectropolarimetric properties of Type Ibc SNe.

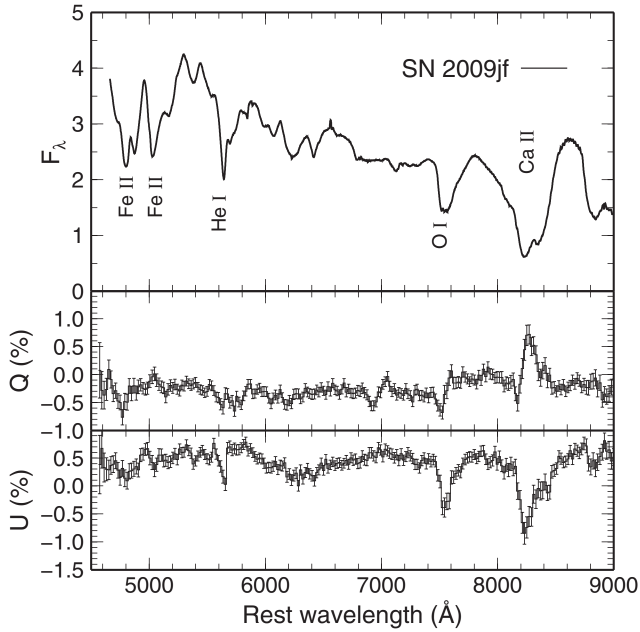

Figure 1. Total flux spectrum and polarization spectrum of SN 2009jf at 9.3 days after maximum. The total flux is shown in unit of 10^{-15} erg s^{-1} cm^{-2} Å^{-1}. For the polarization spectrum, the contribution of the interstellar polarization is *not* corrected for.

2. Subaru Spectropolarimetry of SNe 2009jf and 2009mi

We have performed spectropolarimetric observations of Type Ib SN 2009jf and Type Ic SN 2009mi with the Subaru telescope equipped with the Faint Object Camera and Spectrograph (FOCAS, Kashikawa *et al.* (2002)). The data for SNe 2009jf and 2009mi were obtained on UT 2009 October 24.3 (MJD = 55128.3) and 2010 January 8.3 (MJD=55204.3), respectively. These epochs correspond to 9.3 and 26.5 days after the B band maximum (MJD = 55118.96 for SN 2009jf according to Sahu *et al.* (2011), and MJD = 55177.8 for SN 2009mi, based on our observations). More details of the observations are given in Tanaka *et al.* (2012).

Figure 1 shows the observed total flux and polarization spectrum of SN 2009jf. We clearly detect the changes in the polarization at the strong absorption lines, such as He I, O I, and Ca II. The data around the strong lines are shown in the $Q-U$ plane in Figure 2. It is clear that the data at the Ca II and O I lines occupy different regions in the $Q-U$ plane, indicating different spatial distributions between Ca II and O I. Such a difference is also clearly seen in other SNe e.g. Type Ib SN 2008D (Maund *et al.* (2009)) and Type IIb SN 2008ax (Chornock *et al.* (2011)).

A more interesting feature is the shape of the polarization data in the $Q-U$ plane. The Ca II and O I lines in SN 2009jf show a loop at these lines. This means that the polarization angle varies with Doppler velocity. As suggested by e.g. Kasen *et al.* (2003), Maund *et al.* (2007a), Maund *et al.* (2007b), this loop indicates that axisymmetry is broken in the SN ejecta. We also detect a similar (although less significant) loop in SN 2009mi. Loops in the $Q-U$ plane have also been observed in Type Ia SNe (Wang *et al.* (2003a), Kasen *et al.* (2003), Chornock & Filippenko (2008), Patat *et al.* (2009), Tanaka *et al.* (2010)).

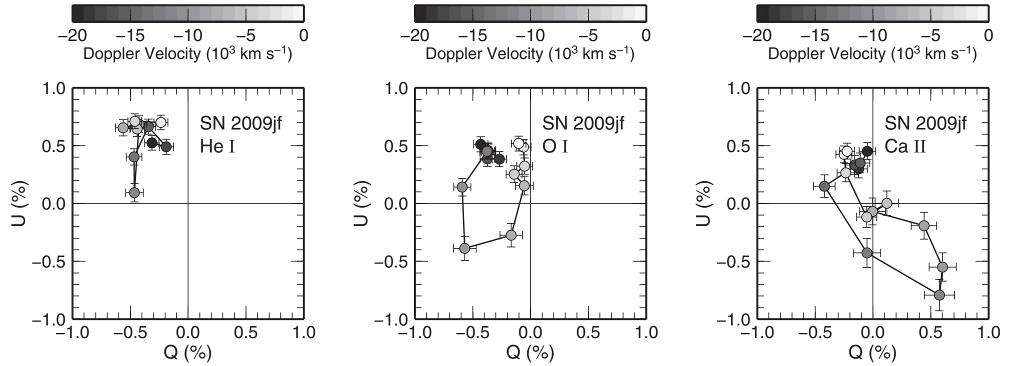

Figure 2. Polarization data of SN 2009jf in the $Q-U$ plane. Data around the He I (left), O I (center) and Ca II (right) lines are shown. Different data points show the polarization at different Doppler velocities as shown in the bar above the plots.

Table 1. Summary of Spectropolarimetric Observations of Type Ibc Supernovae

Object	Type	Loop?	Reference
SN 2005bf	Ib	yes	1,2
SN 2008D	Ib	yes	3
SN 2009jf	Ib	yes	4
SN 2002ap	Ic broad	yes	5,6,7
SN 2007gr	Ic	no	8
SN 2009mi	Ic	yes	4

References: [1]Maund *et al.* (2007a), [2]Tanaka *et al.* (2009a), [3]Maund *et al.* (2009), [4]Tanaka *et al.* (2012) [5]Kawabata *et al.* (2002), [6]Wang *et al.* (2003b), [7]Leonard *et al.* (2002), [8]Tanaka *et al.* (2008)

3. Spectropolarimetric Properties of Type Ibc Supernovae

In Table 1, we list up Type Ibc SNe with high-quality spectropolarimetric data. As also noted by Wang & Wheeler (2008), all SNe show non-zero polarization, which means that stripped-envelope SNe generally have asymmetric explosion geometry. In addition, five SNe out of six show loops in $Q-U$ plane. This implies that a non-axisymmetric, 3D geometry is common in stripped-envelope SNe.

This is somewhat surprising since the line profiles in the nebular spectra, which are another probe of the explosion geometry, are nicely modelled by a bipolar geometry (e.g. Mazzali *et al.* (2001), Maeda *et al.* (2002), Mazzali *et al.* (2005), Maeda *et al.* (2008), Modjaz *et al.* (2008), Tanaka *et al.* (2009b), Taubenberger *et al.* (2009), Maurer *et al.* (2010), but see also Milisavljevic *et al.* (2010)). It must be noted, however, that spectropolarimetry is sensitive to the outer ejecta while nebular line profile is sensitive to the inner ejecta. Thus, for example, 3D perturbation onto a bipolar structure can also be consistent with the observations.

It must be interesting to look for a possible relation between spectropolarimetric properties and nebular line profiles. In fact, we did such an attempt, but could not find any significant correlation because of the small sample size (Tanaka *et al.* 2012). It is important to increase spectropolarimetric samples to further study fully multi-dimensional structure of SNe.

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Discussion

Couch: (Comment) SASI is not necessary to break axisymmetry. Bipolar magnetorotational explosions will break axisymmetry in 3D simulations.

Chornock: I agree that $Q-U$ loops are likely a signature of large-scale structures in the ejecta, but how do you explain the different behaviors of different lines? Do we expect oxygen and calcium to have such different spatial distributions?

Tanaka: Oxygen is synthesized at the pre-SN stage while calcium can be synthesized by the explosion. So, qualitatively, these two elements can have different distributions in the SN ejecta. In fact, helium, which is also synthesized at the pre-SN stage, occupies a similar region to oxygen in the $Q-U$ plane in SN 2009jf.