Testing the magnetar scenario for superluminous supernovae with circular polarimetry


Published in:
Monthly Notices of the Royal Astronomical Society

Document Version:
Publisher's PDF, also known as Version of record

Queen's University Belfast - Research Portal:
Link to publication record in Queen's University Belfast Research Portal

Publisher rights
Copyright 2018 The Author(s)Published by Oxford University Press on behalf of the Royal Astronomical Society. This work is made available online in accordance with the publisher’s policies. Please refer to any applicable terms of use of the publisher.

General rights
Copyright for the publications made accessible via the Queen's University Belfast Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
The Research Portal is Queen's institutional repository that provides access to Queen's research output. Every effort has been made to ensure that content in the Research Portal does not infringe any person's rights, or applicable UK laws. If you discover content in the Research Portal that you believe breaches copyright or violates any law, please contact openaccess@qub.ac.uk.
Testing the magnetar scenario for superluminous supernovae with circular polarimetry

Aleksandar Cikota,1* Giorgos Leloudas,2 Mattia Bulla,3 Cosimo Inserra,4 Ting-Wan Chen,5† Jason Spyromilio,1 Ferdinando Patat,1 Zach Cano,6 Stefan Cikota,7,8 Michael W. Coughlin,9 Erkki Kankare,10 Thomas B. Lowe,11 Justyn R. Maund,12 Armin Rest,13,14 Stephen J. Smartt,10 Ken W. Smith,10 Richard J. Wainscoat11 and David R. Young10

1European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching b. München, Germany
2Dark Cosmology centre, Niels Bohr Institute, University of Copenhagen, Juliane Maries vej 30, 2100 Copenhagen, Denmark
3Oskar Klein Centre, Department of Physics, Stockholm University, SE 106 91 Stockholm, Sweden
4Department of Physics & Astronomy, University of Southampton, Southampton, Hampshire, SO17 1BJ, UK
5Max-Planck-Institut für Extraterrestrische Physik, Giessenbachstraße 1, 85748, Garching, Germany
6Instituto de Astrofísica de Andalucía (IAA-CSIC), Glorieta de la Astronomía s/n, E-18008, Granada, Spain
7University of Zagreb, Faculty of Electrical Engineering and Computing, Department of Applied Physics, Unska 3, 10000 Zagreb, Croatia
8Ruder Bošković Institute, Bijenička cesta 54, 10000 Zagreb, Croatia
9Division of Physics, Math, and Astronomy, California Institute of Technology, Pasadena, CA 91125, USA
10Astrophysics Research Centre, School of Mathematics and Physics, Queens University Belfast, Belfast BT7 1NN, UK
11Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822, USA
12Department of Physics and Astronomy, University of Sheffield, Hicks Building, Hounsfield Road, Sheffield S3 7RH, UK
13Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
14Department of Physics and Astronomy, The Johns Hopkins University, 3400 North Charles Street, Baltimore, MD 21218, USA

Accepted 2018 April 28. Received 2018 April 27; in original form 2018 March 20

ABSTRACT

Superluminous supernovae (SLSNe) are at least ~5 times more luminous than common supernovae. Especially hydrogen-poor SLSN-I are difficult to explain with conventional powering mechanisms. One possible scenario that might explain such luminosities is that SLSNe-I are powered by an internal engine, such as a magnetar or an accreting black hole. Strong magnetic fields or collimated jets can circularly polarize light. In this work, we measured circular polarization of two SLSNe-I with the FOcal Reducer and low dispersion Spectrograph (FORS2) mounted at the ESO’s Very Large Telescope. PS17bek, a fast-evolving SLSN-I, was observed around peak, while OGLE16dmu, a slowly evolving SLSN-I, was observed 100 d after maximum. Neither SLSN shows evidence of circularly polarized light; however, these non-detections do not rule out the magnetar scenario as the powering engine for SLSNe-I. We calculate the strength of the magnetic field and the expected circular polarization as a function of distance from the magnetar, which decreases very fast. Additionally, we observed no significant linear polarization for PS17bek at four epochs, suggesting that the photosphere near peak is close to spherical symmetry.

Key words: supernovae: general – polarization – supernovae: individual: OGLE16dmu, PS17bek.

1 INTRODUCTION

Superluminous supernovae (SLSNe) may include a few remaining examples of deaths of extremely massive stars that in the early universe may have played an important role for re-ionization of the Universe and are therefore an important class of objects to understand. They are extremely bright, as the name would imply, and powering such a luminous display is a challenge. Peak luminosities of SLSNe are greater by a factor of ~5 than peak luminosities of type Ia supernovae, and ~10–100 times greater than broad-lined type Ic and normal stripped envelope supernovae. They are sepa-
rated into two classes: the hydrogen poor SLSN-I, which have quite featureless early spectra; and hydrogen-rich SLSN-II, which are thought to occur within a thick hydrogen shell and are therefore difficult to investigate (Gal-Yam 2012).

Woosley, Blinnnikov & Heger (2007) suggest that collisions between shells of matter ejected by massive stars that undergo an interior instability arising from the production of electron–positron pairs might explain such luminous SLSNe-I (see also Woosley 2016) or a pair-instability explosion of a very massive star (with a core of $\geq 50 \, M_\odot$, e.g. Gal-Yam et al. 2009; Dessart et al. 2013). The luminosity may also be produced by interaction between the ejecta and H-poor circumstellar material (Chatzopoulos, Wheeler & Vinko 2012; Sorokina et al. 2016; Vreeswijk et al. 2017).

Another possibility is that SLSNe-I are powered by an internal engine, such as a magnetar (Kasen & Bildsten 2010; Woosley 2010; Inserra et al. 2013; Nicholl et al. 2013; Chen et al. 2015) or an accreting black hole (Dexter & Kasen 2013). Kasen & Bildsten (2010) have shown that energy deposited into an expanding supernova remnant by a highly magnetic ($B \sim 5 \times 10^{15} \, G$) fast-spinning neutron star can substantially contribute to the SLSN luminosity and explain the brightest events ever seen. They calculated that magnetars with initial spin periods $<30 \, ms$ can reach a peak luminosity of $10^{42} - 10^{45} \, erg \, s^{-1}$ ($M_{bol} = -16.3 \rightarrow -23.8 \, mag$) because of the rotational energy deposition from magnetar spin-down.

In this work, we first time undertake circular polarimetry of SLSNe in the visible part of the spectrum. We aim to test the magnetar scenario using circular polarimetry. Our hypothesis is that if there is a strong magnetic field, we would expect to observe circularly polarized light, attributed to the monotonic grey-body magnetoe missivity which has been theoretically predicted by Kemp (1970) and demonstrated in the laboratory. The challenge for the magnetar observations is that the energy from the magnetar is reprocessed by the ejecta so that the bulk of the luminosity is arising from thermal processes (as is manifest in the spectra). In the thermalization process, the polarization of the original light is destroyed; however, the magnetar’s magnetic field will remain.

Circular polarization has already been observed in white dwarfs with strong magnetic fields. For instance, Kemp et al. (1970) and Angel, Landstreet & Oke (1972) observed strong circular polarization, 1–3 per cent, in visible light, and 8.5–15 per cent in the infrared (Kemp & Swedlund 1970) of Grw+70 8247. For this white dwarf, they estimate a mean projected $B$ field of $1 \times 10^5 \, G$.

Another possible origin of circularly polarized light may be an electron pitch-angle anisotropy in a relativistic jet, for instance from an accreting black hole, as suggested by Wiersema et al. (2013). They observed circular polarization in the afterglow of gamma-ray burst 121024A, which are believed to be powered by a collimated relativistic jet from an accreting black hole.

In Section 2, we describe the targets and observations, in Section 3 the methods, in Section 4, we show the results, which we discuss in Section 5, and the summary and conclusions are presented in Section 6.

2 TARGETS AND OBSERVATIONS

We obtained circular polarimetry of two SLSNe-I at single epochs: OGLE16dmu at 101.3 d past peak (rest frame), and PS17bek at peak brightness. Additionally, we obtained linear polarimetry of PS17bek at four different epochs ($-4.0, +2.8, +13.4,$ and $+21.0 \, d$ relative to peak brightness in rest frame).

All observations in this study were acquired with the FOcal Reducer and low-dispersion Spectrograph (FORS2, Appenzeller 1967; Appenzeller et al. 1998; ESO 2015) mounted at the Cassegrain focus of the UT1 Very Large Telescope (VLT), under the ESO program ID 098.D-0532(A), using the MIT CCD chip. The observations were obtained in the imaging polarimetry mode (IPOL). Circular polarimetry was obtained, without any filters, with two different quarter-wave retarder plate (QWP) angles of $\theta = \pm 45^\circ$ but in two different rotations of the instrument ($0^\circ$ and $90^\circ$) in order to remove possible crosstalks between linear and circular polarization (Bagnulo et al. 2009).

Linear polarimetry of PS17bek was obtained through the V_HIGH FORS2 standard filter ($\lambda_0 = 555 \, nm$, $FWHM = 123.2 \, nm$) at four half-wave retarder plate (HWP) angles ($0^\circ, 22.5^\circ, 45^\circ$, and $67.5^\circ$).

A observation log is given in Table 1.

2.1 OGLE16dmu

OGLE16dmu was discovered on 2016 September 23 (MJD 57654.84) (Wyrzykowski et al. 2016) and classified as a SLSN-I. The classification spectrum is shown in Fig. 1. It is apparently host-less at a redshift $z \sim 0.426$ (Prentice et al. 2016). From GROND observations (Chen et al., in preparation), we determined an apparent magnitude at peak of $m_V = 19.41 \, mag$ in 2016 November 11 (MJD 57698.41). The total Galactic reddening in the direction of OGLE16dmu is $E(B-V) = 0.03 \, mag$ (Schlafly & Finkbeiner 2011), which corresponds to $A_V = 0.07 \, mag$ assuming a Fitzpatrick (1999) extinction law and $R_V = 3.1$. The Galactic reddening-corrected absolute brightness is $M_V = -22.2 \, mag$.

From the rest frame light curve, we estimate the rate of decline at 30 d past maximum (Inserra & Smartt 2014) to be $DM_{30} \sim 0.22 \, mag$. Alternatively, using the metric described in Nicholl et al. (2015a) (the time to reach from maximum light, $f_{max}$, to $f_{max}/e$), we estimate $f_{dec} \sim 70.6 \, d$. Thus, this is a bright and slowly evolving SLSN-I, similar to PT121adam or SN 2015bn.

2.2 PS17bek

PS17bek is a SLSN-I at $z = 0.30992 \pm 0.0003$ (see Fig. 1, PESSTO classification).

It was discovered at $t = 10^4 \, 47m41.90.0$ and $\delta = +26^0 50' 06.0''$ on MJD = 57 802.4 (February 18, 2017) and it is possibly associated to the galaxy GALAXM5C J104 742.19 + 265 006.8. The object was discovered when this region of sky was observed by Pan-STARRS (Chambers et al. 2016; Smartt et al. 2016) in response to a possible low-significance gravitational wave signal provided by LIGO-Virgo (Abbott et al. 2016), but this transient was not considered related to that event. As part of the Public ESO Spectroscopic Survey for Transient Objects (PESSTO), we took a classification spectrum (see Smartt et al. 2015 for details of the instrumentation, calibration, and data access).

We determined an apparent magnitude at peak of $m_V = 19.8 \, mag$ (Cano et al., in preparation) at MJD = 57 814.58. The Galactic reddening in the direction of PS17bek is $E(B-V) = 0.03 \, mag$ (Schlafly & Finkbeiner 2011), which corresponds to $A_V \sim 0.07 \, mag$. Thus, the Galactic reddening-corrected absolute magnitude of PS17bek is $M_V \sim -20.7 \, mag$.

For PS17bek, we estimate a decline rate of $DM_{30} \sim 1.62 \, mag$ or $f_{dec} \sim 23 \, d$. Thus, this is a fast-declining SLSN-I, similar to SN 2010gx or SN 2011ke. In fact, the measured decline rate implies that PS17bek is one of the fastest evolving SLSNe-I (see Inserra et al. 1998).

1We assume a flat universe with $H_0 = 67.8 \, km \, s^{-1} \, Mpc^{-1}$ and $\Omega_M = 0.308$ (Planck Collaboration et al. 2016).
Table 1. Observations log.

<table>
<thead>
<tr>
<th>Name</th>
<th>UT date and time</th>
<th>Filter</th>
<th>(\lambda/2)-plate angle (°)</th>
<th>(\lambda/4)-plate Wollaston angle (°)</th>
<th>Exposure (s)</th>
<th>Seeing (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS17bek</td>
<td>2017-02-25 05:48:09</td>
<td>None</td>
<td>–</td>
<td>315</td>
<td>200</td>
<td>0.61</td>
</tr>
<tr>
<td>PS17bek</td>
<td>2017-02-25 05:53:59</td>
<td>None</td>
<td>–</td>
<td>45</td>
<td>200</td>
<td>0.62</td>
</tr>
<tr>
<td>PS17bek</td>
<td>2017-02-25 06:23:44</td>
<td>None</td>
<td>–</td>
<td>405</td>
<td>200</td>
<td>0.67</td>
</tr>
<tr>
<td>PS17bek</td>
<td>2017-02-25 06:28:02</td>
<td>None</td>
<td>–</td>
<td>135</td>
<td>200</td>
<td>0.61</td>
</tr>
<tr>
<td>PS17bek</td>
<td>2017-02-25 06:42:04</td>
<td>HIGH</td>
<td>0</td>
<td>650</td>
<td>200</td>
<td>0.65</td>
</tr>
<tr>
<td>PS17bek</td>
<td>2017-02-25 07:05:03</td>
<td>HIGH</td>
<td>22.5</td>
<td>0</td>
<td>650</td>
<td>0.66</td>
</tr>
<tr>
<td>PS17bek</td>
<td>2017-02-25 07:16:35</td>
<td>HIGH</td>
<td>67.5</td>
<td>0</td>
<td>650</td>
<td>0.55</td>
</tr>
<tr>
<td>PS17bek</td>
<td>2017-03-06 05:07:26</td>
<td>HIGH</td>
<td>0</td>
<td>700</td>
<td>520</td>
<td>0.71</td>
</tr>
<tr>
<td>PS17bek</td>
<td>2017-03-06 05:16:48</td>
<td>HIGH</td>
<td>45</td>
<td>0</td>
<td>700</td>
<td>0.60</td>
</tr>
<tr>
<td>PS17bek</td>
<td>2017-03-06 05:29:04</td>
<td>HIGH</td>
<td>22.5</td>
<td>0</td>
<td>700</td>
<td>0.59</td>
</tr>
<tr>
<td>PS17bek</td>
<td>2017-03-06 05:41:26</td>
<td>HIGH</td>
<td>67.5</td>
<td>0</td>
<td>700</td>
<td>0.50</td>
</tr>
<tr>
<td>PS17bek</td>
<td>2017-03-20 01:45:38</td>
<td>HIGH</td>
<td>0</td>
<td>700</td>
<td>700</td>
<td>0.64</td>
</tr>
<tr>
<td>PS17bek</td>
<td>2017-03-20 01:58:02</td>
<td>HIGH</td>
<td>45</td>
<td>0</td>
<td>700</td>
<td>0.69</td>
</tr>
<tr>
<td>PS17bek</td>
<td>2017-03-20 02:10:17</td>
<td>HIGH</td>
<td>22.5</td>
<td>0</td>
<td>700</td>
<td>0.70</td>
</tr>
<tr>
<td>PS17bek</td>
<td>2017-03-20 02:22:40</td>
<td>HIGH</td>
<td>67.5</td>
<td>0</td>
<td>700</td>
<td>0.86</td>
</tr>
<tr>
<td>PS17bek</td>
<td>2017-03-20 02:36:04</td>
<td>HIGH</td>
<td>0</td>
<td>700</td>
<td>700</td>
<td>0.68</td>
</tr>
<tr>
<td>PS17bek</td>
<td>2017-03-20 02:48:27</td>
<td>HIGH</td>
<td>45</td>
<td>0</td>
<td>700</td>
<td>0.67</td>
</tr>
<tr>
<td>PS17bek</td>
<td>2017-03-20 03:00:42</td>
<td>HIGH</td>
<td>22.5</td>
<td>0</td>
<td>700</td>
<td>0.77</td>
</tr>
<tr>
<td>PS17bek</td>
<td>2017-03-20 03:13:05</td>
<td>HIGH</td>
<td>67.5</td>
<td>0</td>
<td>700</td>
<td>0.81</td>
</tr>
<tr>
<td>PS17bek</td>
<td>2017-03-30 02:10:19</td>
<td>HIGH</td>
<td>0</td>
<td>500</td>
<td>500</td>
<td>0.69</td>
</tr>
<tr>
<td>PS17bek</td>
<td>2017-03-30 02:19:23</td>
<td>HIGH</td>
<td>45</td>
<td>0</td>
<td>500</td>
<td>0.72</td>
</tr>
<tr>
<td>PS17bek</td>
<td>2017-03-30 02:28:18</td>
<td>HIGH</td>
<td>22.5</td>
<td>0</td>
<td>500</td>
<td>0.68</td>
</tr>
<tr>
<td>PS17bek</td>
<td>2017-03-30 02:37:21</td>
<td>HIGH</td>
<td>67.5</td>
<td>0</td>
<td>500</td>
<td>0.56</td>
</tr>
<tr>
<td>PS17bek</td>
<td>2017-03-30 02:46:59</td>
<td>HIGH</td>
<td>0</td>
<td>500</td>
<td>500</td>
<td>0.47</td>
</tr>
<tr>
<td>PS17bek</td>
<td>2017-03-30 02:56:02</td>
<td>HIGH</td>
<td>45</td>
<td>0</td>
<td>500</td>
<td>0.54</td>
</tr>
<tr>
<td>PS17bek</td>
<td>2017-03-30 03:04:57</td>
<td>HIGH</td>
<td>22.5</td>
<td>0</td>
<td>500</td>
<td>0.58</td>
</tr>
<tr>
<td>PS17bek</td>
<td>2017-03-30 03:13:60</td>
<td>HIGH</td>
<td>67.5</td>
<td>0</td>
<td>500</td>
<td>0.81</td>
</tr>
<tr>
<td>OGLE16dmu</td>
<td>2017-03-30 23:59:36</td>
<td>None</td>
<td>–</td>
<td>315</td>
<td>220</td>
<td>0.74</td>
</tr>
<tr>
<td>OGLE16dmu</td>
<td>2017-03-31 00:04:14</td>
<td>None</td>
<td>–</td>
<td>45</td>
<td>220</td>
<td>0.85</td>
</tr>
<tr>
<td>OGLE16dmu</td>
<td>2017-03-31 00:18:00</td>
<td>None</td>
<td>–</td>
<td>405</td>
<td>220</td>
<td>0.84</td>
</tr>
<tr>
<td>OGLE16dmu</td>
<td>2017-03-31 00:22:38</td>
<td>None</td>
<td>–</td>
<td>135</td>
<td>90</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Figure 1. PESSTO classification spectra of OGLE16dmu (middle blue spectrum) and PS17bek (top red spectrum), compared to LSQ14bdq (bottom green spectrum, Nicholl et al. 2013b). The inset shows the (OIII) and Hβ emission lines in the spectrum of PS17bek, used for the redshift determination. PS17bek and LSQ14bdq have been plotted with a constant offset of +4 \times 10^{-17} and -1 \times 10^{-17}, respectively.

Starting from Gal-Yam (2012), it remains an unresolved issue if H-poor SLSNe can be divided into more sub-classes (e.g. Type I/Type R or fast/slow) and whether this division has physical implications (De Cia et al. 2017; Inserra et al. 2018b; Quimby et al. 2018). Irrespective, it remains an advantage that our experiment probes representative SLSNe from both sub-classes.

3 DATA PROCESSING AND METHODS

The data consist of two science frames per exposure: the upper CHIP1 and lower CHIP2, which correspond to two mosaic parts of the two CCD detectors. In IPOL mode, the image is split by the Wollaston prism into an ordinary (o) beam and an extraordinary (e) beam, and the multi-object spectroscopy slitlets strip mask is inserted to avoid the beams overlapping. The targets were observed at the bottom of CHIP1 (upper frame), centred in the optical axis of the telescope. The bottom strip in the upper frame is the extraordinary beam. The Wollaston prism is usually aligned with the north celestial meridian except when the instrument is rotated by 90° during the second sequence of circular polarimetry, when it was aligned towards East.

All frames were bias subtracted using the corresponding calibration bias frames. A flat-field correction was not performed because the flat-field effect gets cancelled out, because of the redundancy introduced by multiple HWP and QWP angles, for linear and circular polarimetry, respectively (Patat & Romaniello 2006; ESO 2015).
To determine the polarization of our targets, we conducted aperture photometry of sources in the ordinary and extraordinary beams using the IRAF’s DAOPHOT.PHOT package. An optimal aperture radius of ~2 FWHM was used.

3.1 Circular polarimetry

Following the FORS2 user manual (ESO 2015), the amount of circular polarization is given as:

\[
V = \frac{1}{2} \left[ \left( \frac{f^o - f^e}{f^o + f^e} \right)_{\theta = +45^\circ} - \left( \frac{f^o - f^e}{f^o + f^e} \right)_{\theta = -45^\circ} \right],
\]

where \( f^o \) and \( f^e \) are the measured flux in the ordinary and extraordinary beam, respectively, for both quarter-wave retarder plate angles of \( \theta = \pm 45^\circ \). The circular polarization error was calculated by error propagation of the flux errors.

To minimize a possible linear-to-circular polarization crosstalk (Bagnulo et al. 2009), we calculate the average of the Stokes \( V \) measured at two instrument position angles, \( \phi \), and \( \phi + 90^\circ \):

\[
P_v = \frac{V_\phi + V_{\phi + 90^\circ}}{2},
\]

which leads to cancellation of the spurious signal (Bagnulo et al. 2009).

3.2 Linear polarimetry

The Stokes \( Q \) and \( U \) parameters for PS17bek and a number of field stars were derived using the standard approach, as described in Leloudas et al. (2015), that is, via the Fourier transformation of normalized flux differences measured at four half-wave retarder plate angles of 0°, 22.5°, 45°, and 67.5° (see also the FORS2 manual, ESO 2015).

We correct the polarization position angles of the raw measurements for the half-wave plate zero angle chromatic dependence (table 4.7 of ESO 2015), and for OGLE16dmu and PS17bek taken with different instrument position angles, respectively, for both quarter-wave retarder plate angles of \( \theta = \pm 45^\circ \). The circular polarization error was calculated by error propagation of the flux errors.

To determine the linear polarization of our targets, we undertook circular polarimetry for two SLSNe-I: OGLE16dmu and PS17bek at different instrument rotation angles \( \phi \), respectively, for both quarter-wave retarder plate angles of 0° and 90°. The results are summarized in Table 2. The signal-to-noise ratio of PS17bek observed at different instrument rotation angles \( \phi \) of 0° and 90° is \( S/N \sim 272 \) and \( \sim 172 \), respectively, while for OGLE16dmu

\[
\sigma_P = \frac{1}{\sqrt{N SNR}},
\]

where \( N \) is the number of wave plate angles used (Patat & Romaniello 2006).
Figure 3. Sections of the ordinary beams for single imaging polarimetry exposures for OGLE16dmu (left) and PS17bek (right). The top and bottom panels are exposures taken with the instrument rotated by 0° and 90°, respectively. The red circles mark the targets, while green circles mark comparison stars in the field. The radii of the circles correspond to the absolute circular polarization, as indicated in the legend.

Table 3. ISP-corrected linear polarimetry results for PS17bek.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Q (%)</th>
<th>U (%)</th>
<th>Pa (%)</th>
<th>φ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>−4.0</td>
<td>−0.02 ± 0.18</td>
<td>0.05 ± 0.18</td>
<td>0.0 ± 0.18</td>
<td>56.3 ± 97.1</td>
</tr>
<tr>
<td>+2.8</td>
<td>0.1 ± 0.18</td>
<td>−0.13 ± 0.18</td>
<td>0.0 ± 0.18</td>
<td>26.5 ± 31.6</td>
</tr>
<tr>
<td>+13.4</td>
<td>−0.11 ± 0.25</td>
<td>−0.06 ± 0.25</td>
<td>0.0 ± 0.25</td>
<td>74.6 ± 56.8</td>
</tr>
<tr>
<td>+21.0</td>
<td>−0.32 ± 0.46</td>
<td>0.85 ± 0.46</td>
<td>0.19 ± 0.46</td>
<td>55.4 ± 14.5</td>
</tr>
</tbody>
</table>

Notes. aPolarization-bias corrected.

Figure 4. Stokes Q–U plane for PS17bek observed at four epochs. The different colours indicate different epochs: −4.0 (purple), +2.8 (blue), +13.4 (green), and +21.0 (yellow) days relative to peak brightness. The dashed concentric circles of equal polarization have a radius of 0.5 per cent and 1.0 per cent, respectively.

5 DISCUSSION

5.1 Circular polarimetry of OGLE16dmu and PS17bek

In the magnetar scenario, a rapidly rotating magnetar is born during a core-collapse SN explosion. The explosion ejects many solar masses of material, which expands while the magnetar spins down. The spin-down injects $\sim 10^{51}$ erg into the ejected material that has since expanded to a distance of $\sim 100$ au, and heats it up, which then radiates the energy away (Woosley 2010; Kasen & Bildsten 2010; Inserra et al. 2013; Smith 2015).

The idea behind observing a target at early phases was to possibly detect an imprint of the strong magnetic field in the ejected material, while the aim of observing a target at late phases was to observe emitted light originating from the photosphere which moves inwards with time, closer to the magnetar, as the ejecta expands and becomes transparent.

Kemp (1970) predicted that a 'grey-body' model in a magnetic field will emit a fraction of circularly polarized light. The degree of polarization, $q$, is proportional to the emitting wavelength, $\lambda$, and the strength of the magnetic field, $B$ (see equations (7) and (16) in Kemp 1970), and is given by:

$$q(\lambda) \approx \frac{\lambda e B}{4\pi mc}.$$  (3)

where $e$ and $m$ are the electron’s charge and mass, respectively, and $c$ is speed of light.

However, since the magnetic field is decreasing with distance, proportional to $1/\text{distance}^3$, the polarization will drop very quickly. Assuming a magnetic field $B_0$ at the surface of a magnetar with radius $R_0$, the maximum magnetic field decreases as a function of distance, $r$, as following:

$$B(r) = B_0 \left(\frac{R_0}{r}\right)^3.$$  (4)

Fig. 5 shows the magnetic field, $B$, and the circular polarization attributed to grey-body magnetoemissivity, $q$, as a function of distance, calculated in the optical ($\lambda = 0.67 \mu m$), for three different surface magnetic strengths, $B_0$, for a magnetar of radius $R_0 = 10$ km.

For example, assuming a surface magnetic field strength of $B_0 = 5 \times 10^{15}$ G, the magnetic field strength drops to $4 \times 10^{12}$ G at a distance of only $5 \times 10^{3}$ km. The degree of polarization produced by grey-body magnetoemissivity at that distance is $q \sim 0.01$ per cent, which is beyond our detection capabilities.

Furthermore, our observations were taken without any filter in order to achieve a high SNR in a reasonable time, while the absolute degree of circular polarization produced by grey-body magnetoemissivity increases with wavelength (see equation 3). Therefore, it is
of distance, in the continuum (see, e.g. Hoflich 1991; Kasen et al. 2003; Bulla, axis than along the minor axis, which will produce net polarization photons will be scattered by electrons along the photosphere’s major sky. If the projection of the photosphere is not symmetric, more photosphere departure from spherical symmetry projected on the

Intrinsic linear polarization of SNe is a measure of the supernova’s

5.2 Linear polarimetry of PS17bek

Intrinsic linear polarization of SNe is a measure of the supernova’s photosphere departure from spherical symmetry projected on the sky. If the projection of the photosphere is not symmetric, more photons will be scattered by electrons along the photosphere’s major axis than along the minor axis, which will produce net polarization in the continuum (see, e.g. Hoflich 1991; Kasen et al. 2003; Bulla, Sim & Kromer 2015).

Because SLSNe are faint, and thus it is hard to undertake polarimetry that requires high SNR, only a few SLSNe have been studied using polarimetry (Leloudas et al. 2015; Inserra et al. 2016, 2018a; Leloudas et al. 2017; Bose et al. 2018).

LSQ14mo, also a fast-declining SLSN-I (as PS17bek), did not show evidence for significant polarization or polarization evolution from −7 and up to +19 d with respect to maximum (Leloudas et al. 2015). In the contrary, the slowly evolving SN 2015bn did show an increase in polarization with time that was attributed to the photosphere receding to inner layers of the explosion that are more asymmetric. Inserra et al. (2016) obtained the first spectropolarimetric observations of an SLSN-I, at −24 and +28 d, further showing that the geometry was consistent with an axisymmetric configuration (that could be consistent with a magnetar scenario). The polarization increase was confirmed by Leloudas et al. (2017), who obtained multi-epoch imaging polarimetry between −20 and +46 d, showing that the increase was coincident with changes in the optical spectrum.

The result obtained for PS17bek is fairly consistent with the picture obtained from previous events. Similar to the other SLSNe-I, observed around peak, no significant polarization is detected. Our last observation (at +21 d) could be consistent with an increase in polarization but the significance of this result is below 2σ. Either fast-evolving SLSNe (PS17bek and LSQ14mo) follow a different geometrical evolution than slowly evolving SLSNe, or simply the available data, due to a combination of low SNR and lack of data at late phases, are not able to significantly detect an increase in polarization.

6 SUMMARY AND CONCLUSIONS

In this work, we investigated circular polarization of two hydrogen-poor SLSN-I for the first time, using FORS2 at the VLT. Our main results can be summarized as follows:

(i) OGLE16dmu is a slowly evolving hydrogen-poor SLSN. We undertook circular imaging polarimetry at +101.3 d past peak (in rest frame r band) and found no evidence of circular polarization.

(ii) PS17bek is a fast-evolving SLSN-I. We undertook circular polarimetry at −4.0 d relative to the peak brightness (in rest frame r band) and found no evidence of circular polarization.

(iii) Additionally, PS17bek was observed in linear polarimetry mode at four phases (−4.0, +2.8, +13.4, and +21.0 d), and shows no significant linear polarization.

(iv) We cannot exclude the magnetar scenario because of a non-detection of circular polarization, which, due to the rapid decrease in the strength of the magnetic with distance, would be detectable only at small radii close to the surface of the magnetar.

(v) We note that future attempts to measure the strength of magnetic fields using circular polarimetry should be made in the infrared, where the expected degree of circular polarization produced by grey-body magnetoemissivity is higher.

(vi) It is not likely that we will observe circular polarization produced by grey-body magnetoemissivity, because (assuming the magnetar scenario) the bulk of the luminosity arises from thermal processes in the ejecta, which occurs at large distances from the magnetar, where the magnetic fields are not strong enough to produce significant circular polarization, however, such observations are valuable, because they may also allow us to probe for other sources of circular polarization, e.g. relativistic jets.

ACKNOWLEDGEMENTS

We thank Daniele Malesani for useful discussion. This work is on observations made with ESO Telescopes at the Paranal Observatory under the programme ID 098.D-0532(A) and PESSTO (Public ESO Spectroscopic Survey for Transient Objects), ESO programme ID 197.D-1075. SJS acknowledges STFC funding through grant ST/P000312/1. MB acknowledges support from the Swedish Re-
search Council (Vetenskapsrådet) and the Swedish National Space Board. TWC acknowledges the funding provided by the Alexander von Humboldt Foundation. This research was supported by the Munich Institute for Astro- and Particle Physics (MIAPP) of the DFG cluster of excellence "Origin and Structure of the Universe".

REFERENCES

Appenzeller I. et al., 1998, The Messenger, 94, 1
European Southern Observatory, Garching bei München, Germany
Kasen D., et al., 2003, Apj, 593:788
Prentice S. et al., 2016, The Astronomer’s Telegram, 9542
Wyrzykowski L. et al., 2016, Astron. Telegram, 954

This paper has been typeset from a Tex/LaTeX file prepared by the author.