HST optical polarimetry of the Vela pulsar and nebula

P. Moran,1* R. P. Mignani2,3 and A. Shearer1

1Centre for Astronomy, School of Physics, National University of Ireland Galway, University Road, Galway, Ireland
2INAF – Istituto di Astrofisica Spaziale e Fisica Cosmica Milano, via E. Bassini 15, I-20133 Milano, Italy
3Kepler Institute of Astronomy, University of Zielona Góra, Lubuska 2, PL-65-265 Zielona Góra, Poland

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ABSTRACT

Polarization measurements of pulsars offer a unique insight into the geometry of the emission regions in the neutron star magnetosphere. Therefore, they provide observational constraints on the different models proposed for the pulsar emission mechanisms. Optical polarization data of the Vela pulsar was obtained from the Hubble Space Telescope (HST) archive. The data, obtained in two filters (F606W, central wavelength = 590.70 nm and F550M, central wavelength = 558.15 nm), consist of a series of observations of the pulsar taken with the HST/Advanced Camera for Surveys and cover a time span of 5 d. These data have been used to carry out the first high spatial resolution and multi-epoch study of the polarization of the pulsar. We produced polarization vector maps of the region surrounding the pulsar and measured the degree of linear polarization (P.D.) and the position angle (P.A.) of the pulsar’s integrated pulse beam. We obtained P.D. = 8.1 ± 0.7 per cent and P.A. = 146.3 ± 2.4, averaged over the time span covered by these observations. These results not only confirm those originally obtained by Wagner & Seifert and Mignani et al., both using the Very Large Telescope, but are of greater precision. Furthermore, we confirm that the P.A. of the pulsar polarization vector is aligned with the direction of the pulsar proper motion. The pulsar wind nebula is undetected in polarized light as is the case in unpolarized light, down to a flux limit of 26.8 mag arcsec−2.

Key words: polarization – radiation mechanisms: non-thermal – stars: neutron – pulsars: general – pulsars: individual: Crab – pulsars: individual: PSR B0540–69 – pulsars: individual: Vela.

1 INTRODUCTION

Strong polarization is expected when the pulsar optical emission is generated by synchrotron radiation. Shklovsky (1953) suggested that the continuous optical radiation from the Crab nebula was due to synchrotron radiation. This was later confirmed by Dombrovsky (1954) and Vashakidze (1954) who found that the optical radiation was polarized. Incoherent synchrotron emission follows a simple relationship between its polarization profile and underlying geometry. Hence, optical polarization measurements of pulsars provide a unique insight into the geometry of their emission regions, and therefore observational constraints on the theoretical models of the emission mechanisms. From an understanding of the emission geometry, one can limit the competing models for pulsar emission, and hence understand how pulsars work – a problem which has eluded astronomers for almost 50 yr.

Polarimeters are sensitive in the optical, but the majority of pulsars are very faint at these wavelengths with \( V \geq 25 \) (Shearer 2008). Polarimetry in the very high energy domain, X-ray and \( \gamma \)-ray, using instruments on board space telescopes, is of limited sensitivity. So far, detailed results have only been reported for the Crab pulsar (Weisskopf et al. 1978; Dean et al. 2008; Forot et al. 2008). Although the number of pulsars detected in the optical is growing (Mignani 2011), only five pulsars have had their optical polarization measured: Crab (Wampler, Scargle & Miller 1969; Kristian et al. 1970; Smith et al. 1988; Słowikowska et al. 2009; Moran et al. 2013), Vela (Wagner & Seifert 2000; Mignani et al. 2007), PSR B0540–69 (Middleeditch, Pennypacker & Burns 1987; Chanan & Helfand 1990; Wagner & Seifert 2000; Mignani et al. 2010) PSR B0656+14 (Kern et al. 2003), and PSR B1509–58 (Wagner & Seifert 2000). None the less, the optical currently remains invaluable for polarimetry in the energy domain above radio photon energies. The Crab pulsar, being the brightest optical pulsar with \( V \approx 16.8 \) (Nasuti et al. 1996), has had several measurements of its optical polarization, both phase-averaged and phase-resolved. Hence, polarization studies of more pulsars are needed to better understand and constrain the polarization properties of pulsars and search for possible correlations with their intrinsic parameters (e.g. age, magnetic field strength).

The Vela pulsar is a young energetic pulsar, with characteristic age \( \tau \approx 11 \) kyr and spin-down power \( \dot{E} \approx 6.9 \times 10^{36} \) erg s\(^{-1}\), associated with the Vela supernova remnant (SNR; Large, Vaughan & Mills 1968). It is the third brightest optical pulsar \( (V \sim 23.6; \)
2 OBSERVATIONS AND DATA ANALYSIS

2.1 Observations and data reduction

We downloaded the raw HST/ACS polarization science frames of the Vela pulsar field from the Mikulski Archive for Space Telescopes (MAST). The data set is comprised of five observations carried out in five different visits between 2011 February 18 and 23 (Proposal ID: 12240). Observations were obtained using the Wide Field Channel (WFC) detector of the ACS. The WFC employs a mosaic of two $4096 \times 2048$ Scientific Imaging Technologies CCDs, with a pixel scale of $\sim$0.05 arcsec, covering a nominal field of view (FOV) of $\sim$202 $\times$ 202 arcsec$^2$ (Pavlovsky 2004). For these observations, with the polarizers in place, the FOV was $\approx 102 \times 102$ arcsec$^2$. The observations were obtained with three different polarizer elements, POL0V, POL60V, and POL120V, corresponding to rotation angles of 0°, 60°, and 120°, respectively. For each epoch, the integrations were split into pairs of exposures of 1299.5 s each for the POL0V and 1386.5 s each for the POL60V and POL120V. The filter used was the F606W ($\lambda = 590.70$ nm, $\Delta \lambda = 250.00$ nm) for the integrations with the polarizer. Two 1362.5 s exposures with the F550M filter ($\lambda = 558.15$ nm, $\Delta \lambda = 54.70$ nm) and no polarizer in place were taken on 2011 February 18. During each observation, HST pointed at the pulsar at about the same spacecraft roll angle ($\sim$205°), with the pulsar centred at roughly the same CCD position. See Table 1 for a summary of the observations.

For each visit, the raw images, which had already been flat-fielded, were geometrically aligned, combined, and averaged with cosmic ray removal using IRAF (see Fig. 1). We used a total of five field stars and the IRAF task ccmap and the 2MASS catalogue to fit the ACS/WFC astrometry. The pulsar was found at $\alpha = 08^\circ35^\prime20^\prime2578 \pm 0004$, $\delta = -45^\circ10^\prime34^\prime560 \pm 0077$ (the errors denote the rms of the astrometric fit). For each set of observations, the images taken in the different polarizers were analysed using the IMPOL$^2$ software (Walsh 1999), which produces polarization maps (see Fig. 1). In order to increase the number of counts, the size of the cells that we used for the mapping is $\approx0.8 \times 0.8$ arcsec$^2$.

2.2 Polarization measurements

In order to measure its degree of linear polarization, per each observation, we performed aperture photometry of the pulsar in each of the images taken with the POL0V, POL60V, and POL120V polarizer elements using the IRAF task phot. Since one of our goals was to search for possible short-term variability of the pulsar polarization, we preferred not to co-add all the 10 available exposures in each polarizer element (Table 1) but to work on each observation at once. Moreover, since they were performed with slightly different spacecraft roll angles (by $\sim \pm 1^\circ$) and with the pulsar located at slightly different positions on the CCD (by $\sim \pm 2$ pixels), this approach allowed us to deal with possible systematics affecting the measurement of the pulsar polarization and gave us a better handle on the random error estimates.

As done in Moran et al. (2013), we tested our method by performing aperture photometry on a number of reference stars (see Fig. 1) selected to cover uniformly the ACS/WFC FOV, so as to check for possible systematics, such as the dependence of the linear polarization on the star position on the CCD. The stars are not saturated but bright enough to provide good statistics and sample different brightness ranges to check for a possible dependence of the polarization parameters on the star flux. We also wished to verify the size of the aperture to use for polarimetry. We used images taken

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1. https://archive.stsci.edu/
2. http://www.stecf.org/software/IRAFtools/stecf-iraf/impol
Table 1. Summary of the HST/ACS observations of the Vela SNR taken with the WFC. The filters used were F606W ($\lambda = 590.70 \text{ nm, } \Delta \lambda = 250.00 \text{ nm}$) and F550M ($\lambda = 558.15 \text{ nm, } \Delta \lambda = 54.70 \text{ nm}$).

| Date       | Exposure (s) | Filter | Polarizer | Roll angle (PA_V3) (°) | Pulsar position on chip (x, y) |
|------------|--------------|--------|-----------|------------------------|--------------------------------|
| 2011 Feb. 18 | $2 \times 1362.5$ | F550M | CLEAR2L   | 205.9                  | 1167.83, 1169.08              |
|            | $2 \times 1299.5$ | F606W | POL60V    |                        |                                |
|            | $2 \times 1386.5$ |       | POL120V   |                        |                                |
| 2011 Feb. 19 | $2 \times 1299.5$ | F606W | POL0V     | 203.9                  | 1162.19, 1173.87              |
|            | $2 \times 1386.5$ |       | POL60V    |                        |                                |
|            | $2 \times 1386.5$ |       | POL120V   |                        |                                |
| 2011 Feb. 20 | $2 \times 1299.5$ | F606W | POL0V     | 203.9                  | 1162.10, 1174.46              |
|            | $2 \times 1386.5$ |       | POL60V    |                        |                                |
|            | $2 \times 1386.5$ |       | POL120V   |                        |                                |
| 2011 Feb. 21 | $2 \times 1299.5$ | F606W | POL0V     | 204.9                  | 1165.10, 1171.40              |
|            | $2 \times 1386.5$ |       | POL60V    |                        |                                |
|            | $2 \times 1386.5$ |       | POL120V   |                        |                                |
| 2011 Feb. 23 | $2 \times 1299.5$ | F606W | POL0V     | 204.9                  | 1165.29, 1171.90              |
|            | $2 \times 1386.5$ |       | POL60V    |                        |                                |
|            | $2 \times 1386.5$ |       | POL120V   |                        |                                |

Figure 1. HST image of the Vela pulsar field taken with the ACS/WFC on 2011 February 18 with the F606W filter and the POL0V polarizer. The FOV is $\approx 102 \times 102 \text{ arcsec}^2$. The frame has been aligned north–south. The location of the pulsar is marked by the red circle. The reference stars used for analysis are also marked with magenta circles and labelled. The observed polarization vector map is superimposed in black. The legend shows the vector magnitude for 50 per cent polarization. Lastly, the Chandra ACIS (1–8 keV) X-ray contours of the Vela X-ray PWN are overlaid in blue (Pavlov et al. 2003).

on 2011 February 18 but with the F550M filter and no polarizer in place (see Table 1). To maximize the signal-to-noise (S/N), we used an aperture of radius 0.2 arcsec to measure the flux from the pulsar. We measured the sky counts using an annulus of width $\approx 0.1$ arcsec, located 0.15 arcsec beyond the central aperture. Then, we applied an aperture correction to our photometry measurement. We then compared the F550M flux of the pulsar with that of Mignani & Caraveo (2001), obtained using the HST/Wide Field Planetary Camera 2 (WFPC2) and the F555W filter ($\lambda = 550 \text{ nm, } \Delta \lambda = 120 \text{ nm}$), and found consistency once the difference between the two filters is taken into account.

To calculate the Stokes parameters, and hence the degree of linear polarization (P.D.) and position angle (P.A.), we employed the formulae of Pavlovsky (2004) and followed the same approach as
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8.1 ± 1985
6.3 118.4 ± 1 ± 1.3 113.0
Polarization P.A.s (°) of the Vela pulsar and reference stars as a function of time. The errors for the pulsar are purely statistical, whereas those of the stars are the conservative estimate (≈1 per cent) imposed by the debiasing correction (Simmons & Stewart 1985).

| Date        | Vela      | Star 1 | Star 2 | Star 3 | Star 4 | Star 5 | Star 6 | Star 7 | Star 8 | Star 9 | Star 10 |
|-------------|-----------|--------|--------|--------|--------|--------|--------|--------|--------|--------|---------|
| 2011 Feb. 18| 6.6 ± 0.9 | 2.7 ± 1.0 | 1.5 ± 1.0 | 2.0 ± 1.0 | 2.1 ± 1.0 | 2.7 ± 1.0 | 1.7 ± 1.0 | 2.2 ± 1.0 | 1.1 ± 1.0 | 1.8 ± 1.0 | 3.1 ± 1.0 |
| 2011 Feb. 19| 10.2 ± 1.0 | 1.4 ± 1.0 | 1.4 ± 1.0 | 1.6 ± 1.0 | 0.9±1.0 | 2.5 ± 1.0 | 0.7±1.0 | 2.1 ± 1.0 | 0.8±1.0 | 1.3 ± 1.0 | 1.8 ± 1.0 |
| 2011 Feb. 20| 8.2 ± 0.9 | 1.0 ± 1.0 | 0.9±1.0 | 1.7 ± 1.0 | 2.3 ± 1.0 | 2.6 ± 1.0 | 1.4 ± 1.0 | 1.8 ± 1.0 | 2.5 ± 1.0 | 2.3 ± 1.0 | 2.2 ± 1.0 |
| 2011 Feb. 21| 7.2 ± 0.9 | 0.5±1.0 | 0.1±1.0 | 1.8 ± 1.0 | 3.9 ± 1.0 | 2.1 ± 1.0 | 1.3 ± 1.0 | 1.4 ± 1.0 | 1.6 ± 1.0 | 1.7 ± 1.0 | 2.8 ± 1.0 |
| 2011 Feb. 23| 8.4 ± 0.9 | 0.1±1.0 | 0.3 ± 1.0 | 1.3 ± 1.0 | 2.7 ± 1.0 | 1.3 ± 1.0 | 1.6 ± 1.0 | 0.7±1.0 | 1.2 ± 1.0 | 1.4 ± 1.0 | 1.8 ± 1.0 |

Table 3. Polarization P.A.s (°) of the Vela pulsar and reference stars as a function of time. Reported errors are purely statistical.

3 RESULTS

In this section, we present the measurements of P.D. and P.A. for both the Vela pulsar and each of the reference stars in Fig. 1, obtained per each of the five observing epochs. The values of P.D. and P.A., together with their associated errors, are summarized in Tables 2 and 3 inclusive. For an easier visualization of the results, and to make a trend analysis easier, we have also plotted the values of P.D. and P.A. for both the Vela pulsar and each of the reference stars as a function of time (see Figs 2 and 3).

3.1 The pulsar

As seen from Fig. 1, the Vela pulsar is clearly detected in polarized light, both in the POL0V and with the other polarizer elements. The P.D. values of the Vela pulsar measured at the different epochs vary from a minimum of 6.6 per cent to a maximum of 10.2 per cent, the latter corresponding to the second observation. The differences between these values are not statistically significant being, in most cases, within 3σ. The same is true for the P.A. values. We have computed mean P.D. and P.A. values for the Vela pulsar using the methods described in Section 3.1.

3.2 The nebula

The Vela PWN is not detected in polarized optical light in any of the single observations, neither with the POL0V (Fig. 1) nor with any of the other polarizer elements (POL60V, POL120V), in Moran et al. (2013). Sparks & Axon (1999) have investigated the achievable accuracies using the assumption of three perfect polarizers oriented at the optimal 60° relative P.A.s (like the ACS/WFC). They found that the important parameter in experiment design is the product of expected fractional polarization and S/N (p × (S/N)j). For the fractional polarization, p, is just the inverse of the S/N per image. Below are the formulae used for calculating the error in P.D. (equation 1) and P.A. (equation 2; Pavlovsky 2004):

\[
\log \left( \frac{\sigma_p}{p} \right) = -0.102 - 0.9898 \log (p \times (S/N)_i) \quad (1)
\]

\[
\log \sigma_\theta = 1.514 - 1.068 \log (p \times (S/N)_i) \quad (2)
\]

where (S/N)_i is the average target S/N of the three input images, taken with the three different polarizers.

As a guide to our analysis, we also analysed a number of reference stars selected in the pulsar field (see Fig. 1) to confirm the methodology which we used. As in the case of the pulsar, we used an aperture of radius 0.2 arcsec to measure the flux from each star. The sky counts were measured using an annulus of width ≈0.1 arcsec, located 0.15 arcsec beyond the central aperture. Aperture correction was applied for the pulsar. We also investigated the effects of photometric losses due to charge transfer efficiency (CTE) in the CCDs of the WFC. The ACS team claim that there is no evidence of photometric losses due to CTE for WFC data taken after 2004 (see Pavlovsky 2004). None the less, we applied the correction for CTE to our photometry of both the Vela pulsar and the reference stars, and found that it does not change the results of the polarimetry.

An important property of polarization that needs to be considered during our analysis is that of bias. This is due to instrumental errors which tend to increase the observed polarization of a target with respect to its true polarization. The effect is negligible when η = p × S/N is high (>10), where p is the fractional polarization of the target and S/N is the target signal-to-noise per image. See for example fig. 4 of Sparks & Axon (1999). Since the Vela pulsar is in the high-η regime, the debiasing correction is small and therefore we omit it. However, this is not the case for the reference stars which have low measured polarization (<3 per cent and mostly <2 per cent); consequently the associated errors should be ≈1 per cent (Simmons & Stewart 1985) and can be considered to be zero, and hence have low η. See Section 3.1.
with the polarized sky background apparently looking uniform. The ACS/WFC polarization map (Fig. 1) shows the variation of the polarization vectors in the pulsar field and in the vicinity of the pulsar itself. Each vector has magnitude equal to the degree of polarization computed over cells of size $\approx 0.8 \times 0.8$ arcsec$^2$, and its orientation corresponds to the P.A. measured at that point. Such a map allows one to visualize the direction of the magnetic field lines within the region surrounding the pulsar. From Fig. 1, one can see that the pulsar field is significantly polarized, at the level of P.D. $\approx 10$ per cent per cell. However, we cannot see any obvious variation, neither in intensity nor in direction, in the polarization vectors in the vicinity of the pulsar. This is consistent with the fact that the PWN is not detected in polarized light. This is clearly demonstrated in Fig. 1, where we display the ACS/WFC polarization map with superimposed X-ray contours of the PWN in the 1–8 keV energy range as observed by the Chandra-ACIS detector (Pavlov et al. 2003). The figure clearly shows that there is no significant change in the polarization vectors along the main structures of the X-ray PWN, such as the inner and outer arcs and the jets south-east of the pulsar. Unfortunately, owing to the smaller FOV of the ACS/WFC with the polarizer optics in, and the chosen observing strategy, with the Vela pulsar at the centre of the detector, some parts of the region covered by the spatial extent of the X-ray PWN are not fully included in the image or are affected by vignetting at the edge of the detector. In particular, it does not include the region of the bright and long jet protruding north-west of the pulsar position. Thus, we cannot say anything about the jet polarization and whether it is variable, like its X-ray flux and morphology (Durant et al. 2013).

In order to increase our sensitivity to the detection of the PWN in polarized light, we co-added all the 30 available exposures taken...
Figure 3. Plots of the P.A. (°) of both the Vela pulsar and the reference stars as a function of time. The solid lines are the mean of the P.A. Mean values and rms are reported on top of each panel.

In each of the three polarizers (Table 1), corresponding to a total integration time of \( \approx 40 \times 10^3 \) s per element. Since the X-ray PWN is extended over scales of tens of arcsec\(^2\), the possible systematics that might have affected the measurement of the pulsar polarization, such as the slightly different spacecraft roll angle and the pulsar centring on the CCD (see Section 3.1), are much less important here. After co-adding all these exposures, subtracting the field stars, and smoothing with a median filter of 1 arcsec, we found no evidence of the PWN. At the same time, we found no significant difference in the magnitude and orientation of the polarization vectors of the sky background, meaning that its polarization properties do not change on time-scales as short as a few days, as expected.

We use the value of the sky to determine the upper limit of the optical surface brightness of the Vela PWN. For this measurement, we first used a total of 200 cells, each of which was of 1 arcsec\(^2\) area, and evenly spread across the area coinciding with the central part of the X-ray PWN and well away from field stars. After measuring the flux of the sky in each cell, we took the mean of these 200 measurements, which yielded a value of 23.6 mag arcsec\(^{-2}\). We then used this mean in conjunction with the standard deviation of the flux measurements to determine the upper limit of the surface brightness of the Vela PWN. The 3\( \sigma \) upper limit of the PWN is 26.8 mag arcsec\(^{-2}\). Due to the limited FOV of these observations (see Fig. 1), there is no means of determining a background outside the area covered by the PWN. Hence, we note that this is quite a conservative upper limit.

4 DISCUSSION

We have studied the phase-averaged polarization properties of the Vela pulsar using archival HST/ACS data. We have produced polarization vector maps of the \( \approx 102 \times 102 \) arcsec\(^2\) region directly surrounding the pulsar, covering most of the spatial extent of the X-ray PWN, and measured the degree of linear polarization and the
P.A. of the pulsar’s integrated pulse beam. This work marks the first high spatial resolution multi-epoch study of the variability of the polarization of the pulsar.

The results for the Vela pulsar are P.D. = 8.1 ± 0.6 per cent and P.A. = 146.3 ± 2:4 (see Table 4). These values firmly confirm those of Wagner & Seifert (2000) and Mignani et al. (2007), both obtained using the same VLT data set but reported with different error estimates [see Mignani et al. (2007) for a discussion of this discrepancy]. However, our measurements are of greater precision than those previously reported owing to the longer integration time and better spatial resolution of the HST observations. Thus, we obtained the first fully independent, and most accurate measurement of the Vela pulsar polarization in the optical. We could see no evidence of significant variation of the pulsar polarization over the 5 d covered by the HST observations (Table 1), suggesting that the optical polarization of pulsars does not vary over short time-scales. This is also the case of the Crab, whose polarization, also measured with the ACS, does not change up to time-scales of a few weeks (Moran et al. 2013). Nothing can be said for PSR B0540–69, the third pulsar for which optical polarization has been measured by the HST (Mignani et al. 2010). Indeed, in that case the polarization measurement was obtained with the WFPC2 and, because of the different instrument observing strategy in polarization mode, the data set did not consist of a series of repeated measurements at each polarizer angle. Monitoring the polarization of these pulsars on a regular time frame would be important to spot possible secular changes. In addition, phase-resolved polarization measurements, so far carried out for the Crab pulsar only (Słowikowska et al. 2009), would be important to track any change in the pulsar polarization properties following a glitch, or in coincidence with giant pulses.

As in the case of Mignani et al. (2007), we have found an apparent alignment between the phase-averaged polarization direction of the Vela pulsar (P.A. = 146.3 ± 2:4), the axis of symmetry of the X-ray arcs and jets observed by Chandra, which are at a P.A. of 310° ± 1:5 (Helfand et al. 2001), and its proper motion vector (301° ± 1:8) measured with the very long baseline interferometry (Dodson et al. 2003b). This alignment is shown in Fig. 4, where the orientation of these three vectors is compared with the phase-averaged polarization direction measured by Mignani et al. (2007) with the VLT. Interestingly enough, Moran et al. (2013) have found the same scenario for the Crab pulsar. This suggests that the ‘kick’ given to neutron stars at birth, at least in the case of the Crab and Vela pulsars, is directed along the rotation axis (Lai, Chernoff & Cordes 2001), assuming that this is aligned with the proper motion vector. The alternative view is that the apparent alignment is an effect of projection on to the sky plane, and that there is no physical jet along the axis of rotation (Radhakrishnan & Deshpande 2001). More concrete measurements of the optical polarization of pulsars will yield the needed observational restraints on these hypotheses. For the other best candidate, PSR B0540–69, very little can be said because the X-ray structure of the PWN is not clearly resolved by Chandra owing to the Large Magellanic Cloud distance. Moreover, the pulsar has no measured proper motion to compare with (Mignani et al. 2010). Interestingly enough, however, the optical structure of the PWN, which broadly traces that of the X-ray PWN detected by Chandra, shows a possible alignment between its major axis and the pulsar polarization vector. If the PSR B0540–69 PWN has indeed an arc-like structure along its major axis, this would suggest a possible different scenario with respect to both Crab and Vela.

Our improved measurement of the Vela pulsar polarization does not affect the results presented in Mignani et al. (2007) about the comparison with the expectations of various pulsar magnetosphere models. For instance, using the same code as used in Mignani et al. (2007) and the same model parameters, the outer gap model (Romani & Yadigaroglu 1995) still predicts values of the phase-averaged P.D. that are typically much larger than the observed one, unless some depolarization effects are introduced. In particular, our value of P.D., together with its currently associated error, makes it still difficult to set very accurate constraints on the dipole inclination angle α, assuming a realistic viewing angle ζ ~ 65° compatible with the profile of the pulsar optical light curve (e.g. Gouiffes 1998). This is because the values of the phase-averaged P.D. predicted by the outer gap model are much less dependent on α in the low-polarization regime (see fig. 3 of Mignani et al. 2007). According to our measured P.D. = 8.1 ± 0.6 per cent, we can only say that

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|}
\hline
P. D. (per cent) & P. A. (°) & \textit{m}_{\textit{F550M}} & S/N \\
\hline
Pulsar & 8.1 ± 0.6 & 146.3 ± 2.4 & 23.604 ± 0.018 & 60 \\
Star 1 & 1.1 ± 0.5 & 135.5 ± 22.4 & 20.430 ± 0.004 & 543 \\
Star 2 & 1.3 ± 0.2 & 147.7 ± 10.3 & 19.600 ± 0.004 & 1085 \\
Star 3 & 2.4 ± 0.4 & 119.7 ± 3.8 & 21.034 ± 0.005 & 362 \\
Star 4 & 1.7 ± 0.3 & 134.9 ± 12.3 & 19.520 ± 0.004 & 1085 \\
Star 5 & 2.1 ± 0.3 & 135.3 ± 8.6 & 19.903 ± 0.004 & 1085 \\
Star 6 & 1.2 ± 0.2 & 146.1 ± 20.3 & 19.824 ± 0.004 & 543 \\
Star 7 & 1.8 ± 0.2 & 129.2 ± 5.8 & 18.984 ± 0.004 & 1085 \\
Star 8 & 1.5 ± 0.3 & 121.4 ± 5.0 & 21.446 ± 0.006 & 271 \\
Star 9 & 1.9 ± 0.2 & 124.1 ± 1.0 & 21.374 ± 0.005 & 271 \\
Star 10 & 2.3 ± 0.3 & 134.5 ± 4.7 & 19.249 ± 0.004 & 1085 \\
\hline
\end{tabular}
\caption{Overall results for the P.D. (per cent) and P.A. (°). The values listed in the table are the mean and standard error of the P.D. and P.A. The last columns give the star magnitude in the \textit{F550M} filter (\textit{m}_{\textit{F550M}}) and the S/N. Photometry errors are purely statistical.}
\end{table}
the dipole inclination angle $\alpha$ would be probably close to $\approx 80^\circ$. Similarly, the comparison of our measured $\text{P.A.} = 146.3 \pm 2.4$ with that predicted by the outer gap model would imply, for the same model parameters as before, that the P.A. $\psi_0$ of the pulsar’s projected rotational axis would be $\approx 130^\circ$ (see fig. 4 of Mignani et al. 2007). Modulo $180^\circ$, this value is strikingly close to the P.A.s of the axis of symmetry of the X-ray arcs and jets ($310^\circ \pm 1.5$; Helfand et al. 2001) and of the proper motion vector ($301^\circ \pm 1.8$; Dodson et al. 2003b).

Examining the polarization vector maps (see Fig. 1), one can see that both the levels of linear polarization and P.A.s in the vicinity of the pulsar, including the inner part of the X-ray PWN region, are not much different from those of the rest of the field. In other words, the sky around the pulsar is more or less uniformly polarized. In order to quantify the mean sky polarization properties in the Vela pulsar field, we built the histograms of the distributions of P.D. and P.A., which we show in Figs 5 and 6, respectively. The values represented in the histograms are those extracted from the polarization map (Fig. 1), and are computed over cells of $\approx 0.8 \times 0.8$ arcsec$^2$, evenly distributed in the FOV and far from the regions at the edge of the detector, which are affected by vignetting. From the histogram of the P.D. distribution, we see that, on average, the sky is more strongly polarized than the pulsar, with a peak value of P.D. $\approx 12$ per cent. Furthermore, from the histogram of the P.A. distribution, we also see that the polarization P.A. of the pulsar ($\approx 140^\circ$) is away from the peak of the sky distribution ($\approx 71^\circ$). This shows that the polarization properties of the pulsar are different from those of the rest of the field.

From analysis of the geometry of the $HST$/ACS pointing (via the header files), we found that the plane of the scattering is perpendicular to the mean of the distribution of polarization P.A.s in the pulsar field ($\approx 71^\circ$) (see Figs 6 and 7). Hence, this, together with the sky brightness ($\approx 23.6$ mag arcsec$^{-2}$), indicates that these observations are affected by zodiacal light. Furthermore, it suggests that the high level of sky polarization is mostly due to zodiacal light rather than the nebula.

The non-detection of the Vela PWN even in deep $HST$ exposures means that it is intrinsically much fainter in the optical than the Crab and PSR B0540–69 PWNe. This can be due to the fact that either the optical brightness of PWNe is not uniquely related to the pulsar spin-down power, with some pulsars injecting larger fractions of their spin-down power in the acceleration of relativistic particles that powers the PWN emission, and/or it is not uniquely related to the PWN X-ray luminosity.

Finally, it is also possible that the low optical surface brightness of the Vela PWN is also affected by the different physical conditions in the ejecta of the surrounding SNR, such as the local density, and/or by the intensity and properties of its magnetic field, which might lead to a different confinement of the pulsar relativistic wind. A better characterization of the SNR environment in the proximity of the pulsar would be crucial to verify this possibility.

5 CONCLUSIONS

We have studied the phase-averaged polarization properties of the Vela pulsar using archival $HST$/ACS data covering a time span of 5 d. Our work marks the first high spatial resolution multi-epoch study of the polarization properties of the pulsar. We found that the pulsar is polarized, with P.D. $= 8.1 \pm 0.6$ per cent and P.A. $= 146.3 \pm 2.4$, and that its polarization properties do not change significantly over the short time span covered by the $HST$ observations. Our measurement independently confirms those obtained by Wagner & Seifert (2000) and Mignani et al. (2007), using the same VLT data set, but are of greater precision. Thus, we confirm that important
depolarization factors need to be taken into account to make the measured polarization value consistent with the expectation of most pulsar magnetospheres models, such as the outer gap model. Future phase-resolved optical polarization observations of the Vela pulsar, never performed so far, will bring more information on the geometry of the pulsar emission regions, crucial for a better comparison with theoretical models, together with the development of more advanced simulation codes. For example, McDonald et al. (2011) have developed an inverse mapping approach for determining the emission height of the optical photons from pulsars. It uses the optical Stokes parameters to determine the most likely geometry for emission, including magnetic field inclination angle (α), the observer’s line-of-sight angle (γ), and emission height.

As in the case of Mignani et al. (2007), we found an apparent alignment between the P.A. of the Vela pulsar phase-averaged polarization vector, the axis of symmetry of the arcs of the X-ray PWN, and the proper motion vector and spin-axis vector, as observed in the Crab PWN (Moran et al. 2013). Whether this characteristic is unique to all young pulsar/PWN systems cannot be determined at the moment, owing to the lack of a sufficiently representative sample, with Vela being only the third young pulsar with a detected X-ray PWN, a measured pulsar proper motion, and a determined phase-averaged polarization direction.

Finally, we present the first and deepest polarized images of the environment surrounding the Vela pulsar. We found that the PWN is undetected in polarized light as is the case in unpolarized light, down to a limit of 26.8 mag arcsec$^{-2}$, not quite as deep as that obtained by Mignani et al. (2003, 28.1 mag arcsec$^{-2}$) with the WFPC2.

The intrinsic faintness of the Vela PWN with respect to the Crab cannot be easily explained in terms of the pulsar energetics and lower surface brightness of the X-ray PWN, assuming that the X-ray and optical PWN brightnesses are uniquely related to each other, but is probably associated with a dramatic spectral turnover of the PWN between the X-rays and the optical.

From a general stand point, more multil wavelength polarization observations of pulsars, both phase-averaged and phase-resolved, and of their PWNe with existing instruments, such as the HST/ACS and GASP in the optical or INTEGRAL/IBIS in soft γ-rays, and instruments aboard future X-ray missions such as the Gravity and Extreme Magnetism Small Explorer (Ghosh et al. 2013) or the X-ray Imaging Polarimetry Explorer (Soffitta et al. 2013) in the X-rays will help to provide the much needed data to constrain current theoretical models of emission from pulsar magnetospheres.

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