Millimetre polarization of the protoplanetary nebula OH 231.8+4.2: a follow-up study with CARMA

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ABSTRACT
In order to investigate the characteristics and influence of the magnetic field in evolved stars, we performed a follow-up investigation of our previous submillimetre analysis of the protoplanetary nebula (PPN) OH 231.8+4.2, this time at 1.3 mm with the CARMA (Combined Array for Research in Millimeter-wave Astronomy) facility in polarization mode for the purpose of a multiscale analysis. OH 231.8+4.2 was observed at ~2.5 arcsec resolution, and we detected polarized emission above the 3σ threshold (with a mean polarization fraction of 3.5 per cent). The polarization map indicates an overall organized magnetic field within the nebula. The main finding in this paper is the presence of a structure mostly compatible with an ordered toroidal component that is aligned with the PPN’s dark lane. We also present some alternative magnetic field configuration to explain the structure observed. These data complete our previous SMA submillimetre data for a better investigation and understanding of the magnetic field structure in OH 231.8+4.2.

Key words: Magnetic fields – polarization – stars: AGB and post-AGB – stars: individual: OH 231.8+4.2.

1 INTRODUCTION
The search for magnetic fields (hereafter B-fields) in evolved low- and intermediate-mass stars, from asymptotic giant branch (AGB) stars to planetary nebulae (PNe), has been boosted in recent years by observations obtained through multiple techniques. The detections of synchrotron emission (Pérez-Sánchez et al. 2013), Faraday rotation (Ransom et al. 2010), maser emission (Amiri, Vlemmings & van Langevelde 2011; Wolak, Szymczak & Gérard 2012; Leal-Ferreira et al. 2013), dust continuum polarization (Sabin, Zijlstra & Greaves 2007), and molecular line polarization (Girart et al. 2012; Vlemmings et al. 2012) have allowed us to determine the configuration and/or strength of the magnetic field.1 All these discoveries are leading to a better understanding of the role magnetic fields play in the dynamics of evolved stars – in particular, the role they play in shaping the circumstellar envelopes in PNe.

In the case of dust grain polarization, the assumption made is that in the presence of a magnetic field, non-spherical spinning dust grains will be aligned with their long axis perpendicular to the B-field lines (Lazarian 2003; Lazarian & Hoang 2007). The inferred magnetic field orientations are therefore obtained by rotating the polarization vectors by 90° allowing us to trace the direction of the magnetic field projected on to the plane of the sky. The polarization measurements at large wavelengths (i.e. from the far-infrared regime and above) are strongly correlated to the mass or intensity of the regions observed in the line of sight and thus the denser/heavier zones will have a larger weight on the determination of the polarization characteristics.

Recently, our team (Sabin et al. 2014, hereafter Paper I) performed a new investigation of the dust continuum polarization in the protoplanetary nebulae (PPNe) CRL 618 and OH 231.8+4.2 at 345 GHz with the Submillimeter Array (SMA), an interferometer of eight 6 m dishes. The array was used in compact configuration (~2 arcsec resolution).

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1 It is worth mentioning that in PNe, contrary to the case of AGB stars (see the work by Lébre et al. 2014), there is still no conspicuous and definite measurements indicating the presence of a B-field at the stellar surface (Leone et al. 2011, 2014; Jordan et al. 2012; Steffen et al. 2014).
The main result of Paper I was the discovery in OH 231.8+4.2 of an ‘X-shaped’ B-field pattern consistent with a poloidal configuration. There were also hints of a toroidal B-field component in the SMA data. The alignment between the magnetic field structure and the $^{12}$CO($J = 3 \rightarrow 2$) molecular outflow indicated a dynamically important field and the possible presence of a magnetic launching mechanism compatible with the magnetocentrifugal models of Blackman et al. (2001) and Blackman (2014).

In an effort to constrain these results we performed a follow-up investigation, this time at 1.3 mm, in order to obtain a multiscale and multiwavelength coverage of this source. The new polarimetric observations provide more complete and spatially extended magnetic field maps that will allow better comparisons with magnetohydrodynamical (MHD) models.

In Section 2, we describe our observations and data reduction, in Section 3 we present the dust continuum and polarization results for OH 231.8+4.2. The discussion, which includes the comparison with the SMA data, and our conclusions are presented in Sections 4 and 5, respectively. Finally, although this paper focused mainly on the source OH 231.8+4.2, we also chose to briefly present in Appendix A the non-conclusive CARMA (Combined Array for Research in Millimeter-wave Astronomy) detection for the other PPN studied in Paper I, namely CRL 618.

2 OBSERVATIONS AND DATA REDUCTION

The observations presented in this article were carried out with the CARMA (Bock 2006). The 15-element array (six 10.4-m and nine 6.1-m antennas) was used in D-configuration, which had baseline lengths between 11 and 148 m, and a resolution of $\sim 2.5$ arcsec at 230 GHz. The 1.3 mm dual-polarization receivers (Hull, Plambeck & Engargiola 2011) were tuned to include both 1.3 mm continuum, the $^{12}$CO($J = 2 \rightarrow 1$) spectral line at 230.538 GHz, and the SiO($J = 5 \rightarrow 4$) line at 217.105 GHz. We used a correlator configuration with six 500-MHz-wide bands to measure the dust continuum, and two 500-MHz-wide band to map spectral-line emission. Our observations were performed in full-Stokes mode, which allowed all four polarization cross-products ($LL$, $RR$, $LR$, $RL$) to be measured in order to derive maps of Stokes $I$, $Q$, $U$, and $V$.

OH 231.8+4.2 was observed on 2013 December 26 and 27. The observing parameters for both sources are summarized in Table 1. It is worth noting the weather conditions during these tracks which was excellent for OH 231.8+4.2.

The gain, passband, and flux calibrations, as well as the full processing up to the map production, were performed with the software MIRIAD (Wright & Sault 1993; Sault, Teuben & Wright 2011). The reduction of CARMA polarization data required two additional steps: XYphase and leakage calibrations. The XYphase calibration corrects for the phase difference between the L- and R-circular receivers and is performed by observing a linearly polarized noise source with known position angle. The leakage calibration corrects any instrumental polarization errors and is done by observing a strong source over a range of parallactic angles. Hull et al. (2013, p. 2) and Hull et al. (2014, p. 3) derived in their survey Telescope Array Doing Polarization (TADPOL) (and for the same configuration used here) a typical band-averaged leakage of around 6 per cent. More detailed information on the leakages can be found in these two references. The full description of polarization observations with CARMA has been thoroughly discussed by Hull et al. (2014).

3 POLARIZATION AND MAGNETIC FIELD IN OH 231.8+4.2

3.1 Continuum polarization

The final continuum map of OH 231.8+4.2 has a synthesized beam size of $\sim 4.6$ arcsec $\times$ 2.4 arcsec with a position angle of 18°. The rms noise derived for the Stokes $I$, $Q$, and $U$ maps was $\sigma_I = 1.7$ mJy beam$^{-1}$ and $\sigma_Q,U = 0.4$ mJy beam$^{-1}$. The 1.3 mm continuum is elongated in the NE–SW direction (partially owing to the extended beam) and expands over $\sim 15.3 \times 8.8$ arcsec$^2$ (see Fig. 1). We detected a peak intensity of $\sim 240$ mJy beam$^{-1}$ centred on the coordinates $\alpha = 07^h42^m 16.950$, $\delta = -14^\circ 42^\prime 49.95$ and a mean flux of $\sim 70$ mJy beam$^{-1}$.

Contrary to the ‘patchy’ structure described in Paper I, the polarized continuum of OH 231.8+4.2 shown in Fig. 2, appears more uniform and extended ($\sim 14.39 \times 7.86$ arcsec$^2$). A comparison of both data sets is discussed in Section 4.1. We measured a peak polarization intensity ($p_{pk}$) of about 3.6 mJy beam$^{-1}$ and a mean of 1.7 mJy beam$^{-1}$ (4.25σ) over the whole polarized region. Based on the careful analysis of the polarized intensity, percentage polarization, and position angle maps, the polarization distribution could

![Figure 1. HST Hα image of OH 231.8+4.2 (in logarithmic scale), with the superimposed CARMA 1.3 mm dust continuum emission (red contours with values of (0.010, 0.022, 0.040, 0.065, 0.100, 0.140, 0.180, 0.220, 0.240) Jy beam$^{-1}$).](https://academic.oup.com/mnras/article-abstract/449/3/2368/1128581/figure1)
Figure 2. Left-hand panel: millimetre polarization map of OH 231.8+4.2. The black contours showing the total dust emission are drawn in steps of 0.0241 Jy beam$^{-1}$ × (0.2, 0.3, 0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9). The grey-scale image indicates the polarized intensity in Jy beam$^{-1}$. Finally, the polarization vectors are drawn as orange line segments; the scale (bottom left) is set to 10 per cent. Right-hand panel: inferred magnetic field map obtained by rotating the original polarization vectors by 90°. The map indicates a generally well organized magnetic field configuration within the whole structure.

Figure 3. Zoomed-in view showing the variation of the polarization position angle orientation. Three regions can be highlighted: region 1 with a mean PA of $-21^\circ \pm 7^\circ$, region 2 with a mean PA of $+34^\circ \pm 7^\circ$ and finally region 3 with a mean PA of $+14^\circ \pm 4^\circ$. Note that we need to add 90° to those numbers to have the magnetic orientation angle. Combined with Fig. 2-right, we observe that while the first two zones are a reminiscent of the upper portion of the X-shaped magnetic structure reported in Paper I, the third zone is a new and interesting element which fits with the ‘dark lane’ or torus of OH 231.8+4.2 (see Section 5).

The most direct path to establish this correlation B-field/outflow is to study the line polarization (and trace the magnetic field)

3.2 Magnetic field versus $^{12}$CO($J = 2 \rightarrow 1$) molecular outflow

The establishment of a correlation between the distribution of magnetic fields and outflow orientations would help determine whether PPN outflows are magnetically launched. Indeed, the conditions for such launching mechanisms have been explained by Blackman et al. (2001), and rely on the presence of a poloidal field at small distance from the central engine and a toroidal field further away (see Paper I). However, we are still hindered by a lack of information on the strength of the magnetic field.
assuming the presence of a Goldreich–Kylafis effect (Goldreich & Kylafis 1981, 1982), which predicts that the emission from rotating molecules can be polarized in the presence of a magnetic field. The strong $^{12}\text{CO}(J = 2 \rightarrow 1)$ line in OH 231.8$+4.2$ (see also Alcolea et al. 2001) is therefore a good candidate to test the relationship between the magnetic field and the outflows. Unfortunately, the line polarization mode is not available yet on CARMA. Therefore, as we did in Paper I, we rely on the comparison between the magnetic field derived from the continuum polarized emission and the direction and distribution of the CO emission line.

Fig. 4 (top panel) shows the superposition of the CO emission on the Hα HST image, and we can immediately see the good correspondence between the blueshifted emission and the northern optical outflow while the redshifted CO outflow, roughly similar in size to its blue counterpart, only traces the interior (inner side) of the larger southern ionized outflow. In terms of polarization, the same Fig. 4 (bottom panel), tends to indicate that the orientation of the ‘magnetic vectors’ in the region 3 from Fig. 3 is globally roughly perpendicular to the redshifted (lower) CO outflow. The low number of ‘magnetic vectors’ corresponding to the blueshifted (upper) CO lobe prevents us from performing any more precise correlation between the magnetic field and the outflow direction.

4 DISCUSSION

The new CARMA millimetre data help to complete our understanding of the magnetic field configuration in OH 231.8$+4.2$.

4.1 CARMA/SMA comparative study

The 1.3 mm data led to more extended maps of continuum intensity and polarization. This allows us to perform a two-scale comparison of the magnetic structure (Fig. 5). We find that the global mean continuum percentage polarization of 3.4 per cent is slightly lower than the 4.6 per cent found with the SMA at $\sim 345$ GHz.

In terms of configuration, the most interesting finding of this study is the detection of a group of organized ‘magnetic field vectors’ globally perpendicular to both the ionized optical and molecular outflows; these orientations would then be coincident with an organized toroidal magnetic field. The presence of this structure is important for understanding how the magnetic field helps channel the outflow and how it affects the dynamics of OH 231.8$+4.2$.

By comparing the information of both the CARMA (with a maximum baseline of $\sim 148$ m) and SMA (with a maximum baseline of $\sim 77$ m) data sets, and the respective polarization maps, we observe that a toroidal magnetic structure, roughly aligned with the

![Figure 4](https://example.com/figure4.png)

Figure 4. Top: $^{12}\text{CO}(J = 2 \rightarrow 1)$ molecular outflow detected with CARMA overlaid on the HST Hα map. The blueshifted lobe is shown as blue contours in steps of 8.137 Jy beam$^{-1}$ km s$^{-1}$ × (−5, −4, −3, −2, −1, 1, 2, 3, 4, 5, 6, 7, 8, 9); the redshifted lobe is shown as red contours in step of 5.386 Jy beam$^{-1}$ km s$^{-1}$ × (−5, −4, −3, −2, −1, 1, 2, 3, 4, 5, 6, 7, 8, 9). Bottom: map of the magnetic field ‘vectors’ superimposed on the $^{12}\text{CO}(J = 2 \rightarrow 1)$ molecular outflow. The grey-scale image traces the dust continuum emission. The best observed pattern is the globally perpendicular alignment of the southern vectors with the redshifted outflow.

![Figure 5](https://example.com/figure5.png)

Figure 5. Distribution of the thermal dust continuum emission at $\sim 345$ GHz in blue (inner distribution–SMA data) and $\sim 230$ GHz in red (outer distribution–CARMA data), overlaid on optical Hα data (HST). The combination of high-resolution data will allow us to perform accurate multiscale magnetic analysis of the PPN (see Section 4).
PPN equatorial plane, is (only) seen at larger scales. In Paper I, we also suggested the presence of a toroidal magnetic structure, but the small set of vectors on which we relied (in the south-west area in the SMA data) were unlikely to belong to such configuration as the resulting torus would have an inclination in disagreement with the equatorial plane. Those vectors seen with the SMA are more likely to be part of the dipole field where the magnetic field lines are bending/curving. We also detected with CARMA what seems to be at first sight a separated poloidal component (north-east side) which could also be associated with a similar poloidal structure observed with the SMA in the northern lobes. However, the fact that those vectors are 'only' seen on the eastern side combined with the possible variation of the vectors distribution in the south, stated in Section 3.1, might also suggest the presence of a single configuration in the form of a helical magnetic field, instead of two distinct field structures. Proper modelling will be necessary to unveil the correct magnetic configuration.

The detected magnetic configurations (and the scales on which they were detected) would be a first step in probing the presence of a magnetic launching mechanism in OH 231.8+4.2, as described by Blackman et al. (2001) regarding PPNs. Further work, mostly modelling, is needed to fully confirm this phenomenon.

4.2 Combined views of the magnetic field in OH 231.8+4.2

OH 231.8+4.2 has been the subject of many polarisation studies. We can cite first the work by Etoka et al. (2009), who investigated the configuration of the 1667-MHz OH maser emission and showed the presence a magnetic field aligned with the outflow at a radius of ~2 arcsec from the central star (matching the SMA scale; Paper I).

Then the high resolution Very Long Baseline Array observations by Leal-Ferreira et al. (2012), with a synthesized beam size of ~1.7 x ~0.9 mas, allowed the detection of 30 H$_2$O masers. Only three spots exhibited linear polarization, ranging from $p = 0.28$ to $p = 1.15$ per cent. Circular polarization was clearly detected in only one of the brightest maser spots, leading to a value of $B_0 = 44 \pm 7$ mG. In this case, no configuration of the field could be accurately determined. The authors derived a surface stellar magnetic field of ~2.5 G assuming a toroidal configuration. But if we assume that while going closer to the central star the field evolved from a mostly toroidal to a poloidal or dipole configuration (as our new results seems to suggest, but still keeping in mind the helical field hypothesis), this would then bring the stellar magnetic field strength to 140 G up to more than 8 kG, respectively (Ferreira, private communication). A deeper magnetic map would help confirm this result.

5 CONCLUSION

We present a study of the dust polarization in OH 231.8+4.2 at 1.3 mm. The investigation follows up on a previous study conducted by our group at submillimetre range, and allows us to obtain a multiscale map of the magnetic field distribution. In the case of OH 231.8+4.2, we successfully observed a globally organized magnetic field pattern in the form of a north-east poloidal section and what appears to be a toroidal configuration well distributed in the south. The presence of two distinct field configurations in the CARMA data is hampered by the geometry of the so-called poloidal field which is only coincident with one side of the outflow.

An alternative explanation is the presence of a single configuration with a helical distribution including both the single-sided poloidal and the toroidal structures.

The components found with CARMA complete those identified with the SMA at smaller scales; thus, we conclude that the magnetic structure of OH 231.8+4.2 would consist of an inner poloidal field that is surrounded by an outer toroidal or possibly helical field. Further MHD modelling will be needed to properly describe the magnetic field configuration in OH 231.8+4.2 and link it (or not) to the signature of a magnetic collimation and launching mechanism.

Much smaller scales (down to 0.5 arcsec) can now be reached with the Atacama Large Millimeter submillimeter Array (ALMA) with its newly available polarization system. The high-resolution ALMA data will allow us to complete our multiscale investigation of the magnetic field closer to the central engine, and to establish the role of the field in the late stages of stellar evolution.

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APPENDIX A: THE PARTICULAR CASE OF CRL 618

While this paper focused on the source OH 231.8+4.2, the PPNe CRL 618 was also observed on 2013 December 28 and 29. The observing parameters are summarized in Table A1.

When a source is very weakly polarized ($P/I \lesssim 0.5$ per cent), very small changes to the leakage terms can cause drastic changes to the resulting polarization position angles across the source. When we analysed the data for CRL 618, we saw position angles that varied by up to 90° from night to night depending on how exactly we reduced the data. The reason for this was that the source was extremely bright at 1.3 mm ($\sim$2 Jy beam$^{-1}$), but was very weakly polarized ($\sim$0.5 per cent polarization at the intensity peak), which caused us to hit a dynamic range limit where the polarization detected at very low levels can be caused by imperfections in the leakage solutions.

The scatter in the real and imaginary parts of the leakage solutions on the two nights was $\sim$0.01, which is larger than normal considering the two consecutive nights period; however, in this case those slight differences led to significantly different maps for $Q$ and $U$. These small changes in leakages had caused virtually no variations in the CARMA polarization maps of protostellar cores (e.g. Hull et al. 2013, 2014; Stephens et al. 2013), which were on average at least a few per cent polarized, and which tended to be much fainter sources where detection of polarization was limited by the system temperature instead of by dynamic range.

We therefore urge caution when interpreting CARMA observations of sources with polarization fractions of $<0.5$ per cent. While the very low polarization percentage limit we find with CARMA is consistent with the value of 0.7 per cent found with the SMA data, we are not able to confidently determine the B-field configuration.

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| Source | CRL 618 |
|--------|---------|
| Phase centre | $\alpha = 04:42:53.6$ |
| | $\delta = 36:05:54.4$ |
| Obs. Date | 2013-12-28 |
| | 2013-12-29 |
| Gain calibrator | 3C 111 |
| | 3C 111 |
| Passband calibrator | 3C 84 |
| | 0510+180 |
| Flux calibrator | 3C 84 |
| | Uranus |
| Total project length (h) | 3.8 |
| | 5.5 |
| Time on source (h) | 2.43 |
| | 3.28 |
| Total opacity | 0.55 |
| | 0.86 |

Note. $a$Opacity at 230 GHz due to phase noise and atmospheric absorption.