Submillimeter polarisation and magnetic field properties in the envelopes of proto-planetary nebulae CRL 618 and OH 231.8+4.2

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ABSTRACT

We have carried out continuum and line polarisation observations of two Proto-planetary nebulae (PPNe), CRL 618 and OH 231.8+4.2, using the Submillimeter Array (SMA) in its compact configuration. The frequency range of observations, 330–345 GHz, includes the CO\((J=3\rightarrow2)\) line emission. CRL 618 and OH 231.8+4.2 show quadrupolar and bipolar optical lobes, respectively, surrounded by a dusty envelope reminiscent of their AGB phase. We report a detection of dust continuum polarised emission in both PPNe above 4σ but no molecular line polarisation detection above a 3σ limit. OH 231.8+4.2 is slightly more polarised on average than CRL 618 with a mean fractional polarisation of 4.3 and 0.3 per cent, respectively. This agrees with the previous finding that silicate dust shows higher polarisation than carbonaceous dust. In both objects, an anti-correlation between the fractional polarisation and the intensity is observed. Neither PPNe show a well defined toroidal equatorial field, rather the field is generally well aligned and organised along the polar direction. This is clearly seen in CRL 618 while in the case of OH 231.8+4.2, the geometry indicates an X-shaped structure coinciding overall with a dipole/polar configuration. However in the later case, the presence of a fragmented and weak toroidal field should not be discarded. Finally, in both PPNe, we observed that the well organised magnetic field is parallel with the major axis of the 12\(^{12}\text{CO}\) outflow. This alignment could indicate the presence of a magnetic outflow launching mechanism. Based on our new high resolution data we propose two scenarios to explain the evolution of the magnetic field in evolved stars.

Key words: magnetic fields – polarization – planetary nebulae: individual: CRL 618, OH231.8+4.2

1 INTRODUCTION

Proto-planetary nebulae (PPNe) are the by-products of low and intermediate mass stars (∼0.8–8 M\(_\odot\)) in transition between the asymptotic giant branch (AGB) and the planetary nebula (PN) phases. At this stage of stellar evolution the central star is not hot enough to fully ionise the still present circumstellar envelope. PPNe therefore have massive molecular and dust shells, relics of past AGB mass loss events. Consequently observational studies based on the thermal emission of the dust continuum and molecular species have been conducted over the years at submillimeter, millimeter and centimetre wavelengths (e.g. Sánchez Contreras et al. 1998, Woods et al. 2005, Bujarrabal et al. 2012). These studies revealed the properties of the dust grains and molecules, the distribution and geometry of the material, and the kinematics of the molecular and dusty winds (leading in some cases to the discovery of fast, i.e. \(\geq 100\) km s\(^{-1}\) outflows).

In contrast, the polarisation of both the dust continuum and molecular lines are still poorly studied. The polarimetric information at these longer wavelengths is primarily used to trace the magnetic field’s geometry and to study anisotropy in the envelope; it also yields information on the dust grains properties (e.g. nature, size). Submm-to-cm polarimetric investigations are then important tools for the understanding of PPNe.

Dust continuum polarisation is based on the principle of alignment of non-spherical spinning dust grains with their long axis (and therefore the polarisation angle) perpendicular to the magnetic field (Lazarian 2003, Lazarian & Hoang 2011). The linearly polarised emission of these grains therefore gives a direct image of the magnetic field distribution/geometry by rotating the polarisation vectors
Submm emission is roughly elongated in the direction of the outflows (observations, superimposed. Both PPNe show a clear asymmetry and the Hubble Space Telescope with their respective dust continuum emission Figure 1. scales (Matthews et al. 2001, 2002).

A field has been studied by Etoka et al. (2009) and Leal-Ferreira et al. Sánchez Contreras et al. (1997), Alcolea et al. (2001). Its magnetic field has been investigated using this method.

The combination of both dust and molecular polarisation is a valuable tool to determine the magnetic field geometry and anisotropy in PPNe. We present such a dual polarimetric study on the circumstellar envelopes of two well-known PPNe: CRL 618 and OH 231.8+4.2.

CRL 618 (also named the Westbrook Nebula) is a ~200 years old (Kwok & Bignell 1984) PPN located at ~0.9 kpc (Goodrich 1991; Sánchez Contreras & Sahai 2004). The nebula is characterised by two pairs of shocked, rapidly expanding lobes (Balick et al. 2013), belonging to the ‘multipolar’ morphological class following Sahai et al. (2005), a central compact HH region and an ancient AGB halo (Sánchez Contreras et al. 2002). CRL 618 is also known for its rich carbonaceous dust and molecular content which have been extensively studied at submillimeter, millimeter and centimeter wavelengths from ground based to space telescopes (Phillips et al. 1992, Nakashima et al. 2007, Bujarrabal et al. 2010, Tafova et al. 2013).

OH 231.8+4.2 (aka the Rotten Egg Nebula or Calabash Nebula) is a slightly older PPN (~770 yr, Alcolea et al. 2001) with a bipolar morphology as illustrated by its two asymmetrical elongated lobes. Similar to CRL 618, the PPN displays an external round halo. The nebula is located at ~1.12 or 1.30 kpc according to Choi et al. (2012) and Kastner et al. (1992) respectively and shelters a binary star system (Main Sequence A-type + Mira (QX Pup) following Sánchez Contreras et al. 2004b). OH 231.8+4.2 has a rich molecular spectrum and an oxygen-rich chemistry, although carbonaceous species such as HCN, HNC and CS are also seen.

Anisotropic radiation alters the molecular magnetic sub-levels. Morris et al. (1985) proposed another explanation and linked the polarisation to a stellar radiation field resulting in a preferential rotational direction for the molecules. The latter hypothesis does not necessarily imply the action of magnetic fields. However contrary to the case of dust polarisation, emission-line polarisation vectors can be either parallel or perpendicular to the magnetic field. The polarisation direction will be strongly affected by the physical conditions within the objects (e.g. radiation field, hydrogen number density, magnetic field). Few evolved objects have been investigated using their polarised molecular lines and the most recent papers focused on AGB stars such as IRC+10216 (Girart et al. 2012) and IK Tau (Vlemmings et al. 2012). PPNe have not yet been studied using this method.

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Our submillimeter investigation is organised as follows. In section §2 we describe the observations and data reduction. Section §3 includes the continuum polarisation results for CRL 618 and OH 231.8+4.2 respectively followed by the line polarisation results. Finally the discussion and concluding remarks are presented in sections §4 and §5 respectively.
2 OBSERVATIONS AND DATA REDUCTION

We observed CRL 618 and OH 231.8+4.2 with the Submillimetre Array (SMA) in polarimetric mode (Rao & Marrone 2005). We used the compact configuration giving a maximum baseline of 77 m. The selected frequency range is divided between the Lower Side Band (LSB) (330–334 GHz) and the Upper Side Band (USB) (342–346 GHz). These ranges were chosen to also cover the CO lines in the J=3–2 transition, i.e. $^{13}\text{CO}$ and $^{12}\text{CO}$, at rest frequencies 330.587 GHz and 345.796 GHz respectively.

The correlator setup provides a spectral resolution of ~0.8 MHz (i.e. 0.70 km s$^{-1}$) at 345.796 GHz. 3C111 was used as gain calibrator and 3C279 as a bandpass and polarisation calibrator for both objects. CRL 618 was observed on 2011 November 28 for 16 hours (including the calibrators) with a telescope phase center $\alpha_{2000}=(4^h22^m53.68^s,\delta_{2000}=+36^\circ06'53.4''$. The weather conditions were excellent with a mean zenith of $\tau=0.045$ at 225 GHz and stable phases during the observations. OH 231.8+4.2 was observed on 2011 December 27 for 14 hours (including the calibrators) with a telescope phase center $\alpha_{2000}=(10^h42^m52.83^s,\delta_{2000}=+14^\circ42'52.1''$. The weather conditions were not optimal due to snow at the summit. The mean $\tau$ was 0.075 (the maximum value reached was 0.13) and the phases were also unstable during the observing run.

The flux, gain and bandpass calibration was performed with the software MIR and then exported to the MIRIAD (Wright & Sault 1993; Sault et al. 2011) for polarization calibration and imaging. Our data were corrected for polarization leakage (i.e. instrumental polarisation); we found for both objects consistent leakage terms of ±5 per cent in the lower sideband and ±2 per cent in the upper sideband consistent for both objects. We also emphasize that a strong polarization calibrator such as 3C279 coupled with a good coverage of parallel angle results in an accuracy of 0.1 per cent in instrumental calibration (Marrone & Rao 2008).

3 RESULTS AND ANALYSIS

The high resolution provided by the SMA allow us to identify different line splitting in both objects which are likely linked to velocity motions as well as the large expansion of the $^{12}\text{CO}(J=3–2)$ molecular line in CRL 618 indicating a fast CO outflow.

3.1 Continuum polarisation

3.1.1 CRL 618

The continuum was carefully selected and subtracted from both the LSB and USB avoiding the inclusion of emission lines such as the relatively strong CO$(J=3–2)$, CS$(J=7–6)$, H$^{13}$CN$(J=4–3)$, HC$_3$N$(J=38–37)$ by visually examining the visibility amplitude spectra. The final maps of the thermal continuum emission in CRL 618 (relative to dust polarisation and magnetic fields) were made combining the line-free channels of the USB and LSB. To obtain the best sensitivity for the Stokes I (total intensity) and Stokes Q and U (linear polarisation), we used a robust weighting (in order to minimise the noise level) resulting in a synthesised beam of $2.2 \times 1.9$ arcsec with a position angle of $-77^\circ.6$. The measured rms noise levels, $\sigma_I=19.8$ mJy/beam and $\sigma_{Q,U}=2.2$ mJy/beam, defined the zero levels we applied to establish the polarisation maps. The polarised intensity and percentage of polarisation ($I_P$ and $P(\%)$ respectively) are defined as the following: $I_P^2=Q^2+U^2-\sigma_{Q,U}^2$ and $P(%)=I_P/I$ (with I the total intensity).

The continuum dust emission was detected over an area of approximately 5.4 × 4.6 arcsec centred at the coordinates $\alpha=04^h42^m53.58^s,\delta=+36^\circ06'53.4''$ (Fig.1). The continuum emission is slightly elongated east-west and this is consistent with the results by Martin-Pintado et al. (1993) (although at higher angular resolution). The measured peak intensity, located in the dark lane of the PPN, is 3.4 Jy/beam with a mean of 1.2 Jy/beam over the full area of the continuum emission.

Linear polarisation is detected above ±σ across the source. The polarimetric information obtained reveals a peak of 9.6 mJy/beam (at $\alpha=04^h42^m53.62^s,\delta=+36^\circ06'53.7''$) and a mean polarised emission of 7.0 mJy/beam which correspond to 4.4σ and 3.2σ detections respectively. The peak continuum intensity is not coincident with the peak fractional polarisation $P(%)=0.7$. However, the mean polarisation over the whole structure is quite low with $P(%)=0.3$. Those values depend on the assumed zero level (derived from the noise level), but we do not expect it to reach values greater than ∼1 per cent.

The polarisation vectors can be divided in two main sets which overall form a slightly curved pattern opening towards the East (Fig.2). The first set is linked to the upper (northern) half of the polarised continuum and shows a mean polarisation angle of ±22°; the second set is linked to the lower (southern) half of the polarised continuum and shows a mean polarisation angle of ±10°. We however have to be careful while discussing the variation in polarization angle as the polarization emission is not spatially resolved, as shown by the size of the synthesised beam. Assuming that the magnetic field direction is given by rotating the dust polarisation vectors, in Fig.2, Left, by 90 degrees, we obtain the magnetic map in Fig.2, Right which we discuss later in this article (§4).

3.1.2 OH 231.8+4.2

The robust weighting applied resulted in a synthesised beam of ±2.5 × 1.9 arcsec with a position angle of −11°.1. The rms noise derived for the Stokes I, Q, and U was $\sigma_I=20.5$ mJy/beam, and $\sigma_{Q,U}=4$ mJy/beam. The thermal emission from the continuum appears as an elongated distribution extending over an area of ±3.5 arcsec$^2$ and centred at the coordinates $\alpha=07^h42^m16.99^s,\delta=−14^\circ42'49.7''$ (Fig.1). The peak intensity (located at the coordinates $\alpha=07^h42^m16.95^s,\delta=−14^\circ42'39.7''$) is 0.78 Jy/beam with a mean of 0.31 Jy/beam over the whole area. The polarised structure in OH 231.8+4.2 strongly differs from that of CRL 618 as it appears fragmented into four parts (Fig.3). The largest component (∼2×1.5 arcsec) is located in the north-east section and shows a peak polarised intensity of 16 mJy/beam (∼4σ; which is not exactly coincident with the peak of Stokes I) and a mean polarised intensity of 11 mJy/beam (∼2.7σ) is measured over this polarised area. The south-east component shows a similar polarised intensity of 16 mJy/beam (mean of 11 mJy/beam) and this is the location of the strong peak percentage of polarisation with a value of ±15.6 per cent (the mean percentage is 6.7 and 4.3 per cent over the whole structure). The north-west and south-west components both show polarised intensities of ∼10 mJy/beam and a mean of ∼9 mJy/beam. We highlight the

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2 The Submillimeter Array is a joint project between the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics, and is funded by the Smithsonian Institution and the Academia Sinica.

3 https://www.cfa.harvard.edu/~cqi/mircook.html
Figure 2. Left: Combined (USB+LSB) polarisation map of CRL 618. Right: Combined magnetic field map derived by rotating the polarisation vectors by 90 degrees. The magnetic field vectors show a geometry which can be linked to a polar field distribution mostly aligned (in the center) with the outflows indicated by the arrows. The red and blue correspond to the red- and blue-shifted CO outflow (see Fig.7 later in this article). In both cases, the black contours which indicate the total dust emission are drawn in steps of 0.02 Jy × (3,6,10,20,40,60,90,120,150). The color image indicates the polarised intensity with its associated scale bar in Jy/beam on the right. Finally the polarisation vectors are drawn as red segments and the scale is set to 1 per cent. The segments are greater than 2.5σ detections with the peak value of 4.4σ. The uncertainty in PA due to thermal noise is about 5 degrees. North is up and East is left. In all maps the polarisation segments were slightly oversampled when exporting the data from MIRIAD–CGDISP display tool to the interactive graphics software WIP (Morgan 1995).

Figure 3. Same as Fig. 2 for OH 231.8+4.2 with Left: Combined (USB+LSB) polarisation map. The continuum contours are drawn in steps of 0.02 Jy × (3,6,10,15,20,30,40,50,60); Right: Combined magnetic field map with the polarisation vectors rotated by 90 degrees. The field’s structure shows an X-shaped (or dipole) configuration. Similarly to CRL 618 the arrows indicate the direction of the (blue and red-shifted CO) outflows. The polarisation vectors are drawn as red segments and the scale is set to 10 per cent.
3.2 Spectral line polarisation

In an attempt to detect molecular line polarisation we also targeted the strongest molecular lines present in both objects: $^{13}\text{CO}(J=3\rightarrow2)$ in the LSB and $^{12}\text{CO}(J=3\rightarrow2)$ in the USB. The SMA spectra are shown in Fig. 4 and Fig. 5 for CRL 618 and OH 231.8+4.2 respectively. We note that recently, Lee et al. (2013) presented a higher resolution ($\sim0.3$ and $\sim0.5$ arcsec) spectrum as well as a slight east-west gradient in the polarised intensity distribution. The intervening positions between the four regions do not have polarization detection above $2.5\sigma$ (which is the cutoff in Stokes $Q$ and $U$ when computing polarization angles for OH231). The partition of the electric vectors is also quite interesting as each component presents not only well organised patterns but also a main position angle (PA) with values and signs different from the immediate neighbor. Indeed, the north-east and north-west spots have global PAs of approximately $-34\pm18^\circ$ and $+57\pm3^\circ$, respectively, the south-east and south-west spots show global PAs of $+70\pm3^\circ$ and $-8\pm5^\circ$, respectively. The derived magnetic field map (Fig. 3-Right) is different than that of CRL 618 due to the fragmented detected polarised emission (see discussion in section §4 ).
Figure 6. $^{12}\text{CO}$ channel maps for CRL 618 (Top) and OH 231.8+4.2 (bottom). The contours are set at 10 per cent of the peak. In the channel maps, the peak of the continuum is represented by the star symbol and the velocity in km s$^{-1}$ is indicated in the top-right corner. Both sets of maps indicate the presence of high velocity gas in the PPNe.
Submm polarisation of CRL 618 and OH 231.8+4.2

4 DISCUSSION

The SMA data obtained indicates the presence of a polarised continuum at submillimeter wavelengths in the proto-planetary nebulae CRL 618 and OH 231.8+4.2. Several observations can be made regarding the dust polarisation in these objects and the magnetic field geometry.

4.1 Grain dust properties

We observed that OH 231.8+4.2 is more polarised on average, in terms of degree of polarisation, than CRL 618 despite its non-uniform coverage. Thus, the mean degree of polarisation in CRL 618 is 0.3 and 4.3 per cent for OH 231.8+4.2. Both objects differ in their chemistry, and Sabin, Zijlstra & Greaves (2007) have shown that in their sample, and at the same wavelength, the mean degree of polarisation of the oxygen-rich PNe/PPNe is greater than that of the carbon-rich PNe/PPNe. The two new nebulae studied here also follow this trend. This supports the idea that the grain alignment efficiency is higher in O-rich than in C-rich envelopes and therefore dust chemistry plays a role not only in the polarisation process but also in our interpretation of magnetic field distribution.

Carbon grains have generally a smaller size than silicate grains and may not produce significant polarisation. Also, it would be easier or more likely for larger grains to host superparamagnetic particles (Jones & Spitzer 1967; Mathis 1986; Kim & Martin 1993), such as iron or magnetite, which would cause a higher level of polarisation and a more efficient dust grain alignment by the magnetic field. The polarised intensity appears to be sensitive to the grain shape as well (Kim & Martin 1995) and most of the dust alignment theories require either elongated (e.g. oblate/prolate spheroids) or irregular grains (Lazarian 2003). Therefore one would expect that the presence in the disk of OH 231.8+4.2 of larger grains with iron inclusions, crystalline olivine (MgSiO$_3$), crystalline enstatite (MgSiO$_3$), and H$_2$O crystalline ices (Maldoni et al. 2004, via modelling), would produce a greater polarisation than CRL 618, which presents carbonaceous dust (mostly amorphous carbon, see Lequeux & Jourdain de Muizon 1990).

Unfortunately a detailed study of the dust grain properties in those objects is still missing.

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Figure 7. Distribution of the $^{12}$CO(J=3→2) outflow vs the magnetic field. Left panel: The blue and red-shifted lobes of the $^{12}$CO emission in CRL 618 are drawn in contours starting at 10 per cent and in steps of 10 per cent of the peak (blue peak = 828 Jy × km s$^{-1}$; red peak = 399 Jy × km s$^{-1}$). The CO outflows are integrated over a velocity range of $-110$ to $-20$ km s$^{-1}$ for the blue-shifted lobe and $+5$ to $+90$ km s$^{-1}$ for the red-shifted lobe. We can therefore see the integrated emission intensity for each element. The two lobes are aligned with the continuum (Stokes $I$) emission (color scale in mJy) and a good agreement is also observed with the magnetic vectors distribution (cyan segments). Right panel: Same as the left panel but for OH 231.8+4.2. In this case, the $^{12}$CO emission contours start at 30 per cent and in steps of 10 per cent of the peak (blue peak = 100 Jy × km s$^{-1}$; red peak = 158 Jy × km s$^{-1}$). The CO outflows are integrated over a velocity range of $-60$ to $+15$ km s$^{-1}$ for the blue-shifted lobe and $+50$ to $+110$ km s$^{-1}$ for the red-shifted lobe. We observed an elongated blue shifted CO emission and a good correlation between the magnetic vectors (black segments) and the general outflow distributions.
4.2 Depolarisation effect

An anti-correlation is seen between the fractional polarisation and the total intensity in both objects. Indeed, $P(\%)$ tends to decrease from the edges to the center of the emission area, opposite to Stokes $I$. This ‘depolarisation effect’ is not new and has often been observed in dark clouds, molecular clouds and star forming regions (e.g. Chen et al. 2012) but also, and most relevant here, in PNe and Post-AGB stars (Sabin, Zijlstra & Greaves 2007; Greaves 2002). This pattern can be associated with multiple phenomena such as the effect of beam smearing, a complex magnetic field distribution (Matthews et al. 2001; Greaves 2002), and a loss of efficiency in the grain alignment (Lazarian et al. 1997) due to molecular collisions or the variation of the density which would alter the structure of the dust grains and therefore the degree of alignment (Cho & Lazarian 2005).

4.3 Dust distribution

As previously mentioned the polarisation indicates the location of aligned dust. In both PPNe this polarised dust is circumscribed inside the optical dark lane.

In CRL 618 the polarised grains are roughly perpendicular to the direction of the ionised outflows (Fig. 2-Left). The emission, expanding over $\simeq 3.8$ arcsec$^2$, might be related to the dusty torus/ring or to the central bipolar compact H$\alpha$ region (Kwok & Bignell 1984; Sánchez Contreras & Sahai 2004, see their Fig.6).

In OH 231.8+4.2 the polarisation vectors, which are divided into four groups, indicate different polarisation angles and seem to draw the contours of a dusty region (if we link them all) which might also delimit a ring or torus of $\simeq 3.6$ arcsec radius well centred on the equator of the PPN (Fig. 3-Left). This distribution appears consistent with the ring-like structure described by the polarisation vectors associated to the OH masers in (Etoka et al. 2009).

4.4 Magnetic field distribution

The magnetic field in CRL 618 is globally aligned with the pairs of ionised outflows (indicated by the arrows in Fig. 2-Right). Indeed the polarisation vectors of the main structure show a mean PA of $\simeq 96^\circ$ while the PPN has a mean PA along the lobes of $\simeq 94^\circ$. The orientation of the magnetic field is mostly at 90 degree to the equatorial plane of CRL 618. This configuration is pretty similar to the structure of CRL 2688, which is another carbon rich PPN with exactly the same optical quadrupolar morphology. CRL 618 therefore shows a well defined polar magnetic field. The magnetic field appears to be well organised.

The field’s distribution in OH 231.8+4.2 is particularly patchy. The eastern side of the PPN (also showing the higher polarisation intensity) presents in each small area a very well organised curved field directed away from the equatorial plane (Fig. 3-Right). The magnetic vectors describe at first sight an X-shape which would then associate the magnetic field in OH 231.8+4.2 with a dipole configuration (see model by Padovani et al. 2012). However, we cannot discard another interpretation that is the low inclination respected to the equatorial plane of some vectors belonging to the north-west and south-east blobs (and to some extent the south-west blob), might indicate the presence of a partial (and not strongly delineated) toroidal field. OH 231.8+4.2 would in this case show a dual configuration such as the PPN CRL 2688.

It is interesting to notice that neither of these two high mass nebulae show a well defined and constrained toroidal equatorial magnetic field such those seen in the planetary nebulae NGC 6537, NGC 6302 and NGC 7027, which in turn show no poloidal field (Sabin, Zijlstra & Greaves 2007). But they coincide more with the magnetic distribution of CRL 2688 where the field is mainly aligned with the polar direction. CRL 618, OH 231.8+4.2 and CRL 2688 being younger than the ‘NGC group’, we may see here a correlation with the evolutionary stage of the nebulae. This would then indicate that there is either a tendency for the distribution of the magnetic field to evolved from a single dipole/poloidal configuration to a toroidal one (passing through a phase of dual configuration) while the nebulae evolve (Fig. 8-Case a). This type of transition generally occurs via the mechanism of rotation. An alternative is that both configurations might exist simultaneously (Fig. 8 Case b). In this case we postulate that the initially weak toroidal field (as it is often the case in slow rotator objects) could coexist with a stronger poloidal one. As the nebula expands, the later declines quickly, as $r^{-2}$, respective to the toroidal field which begins to dominate because it declines as $r^{-1}$. This would explain why no poloidal configuration is seen in more evolved nebulae e.g. PNe (see also Gardiner & Frank 2001).

A greater statistical sample and a multi-scale analysis of the magnetic field distribution are still needed to answer the ‘evolutionary problem’.

So how do magnetic fields account for the bipolar or multipolar shapes observed? As we observed non-spherical geometry before the occurrence of the toroidal fields the latter cannot be the main dynamically shaping agent, i.e. with enough energy to constrain the material in the equatorial plane and launch collimated outflows. However it has been theoretically claimed that dipole magnetic fields can as well lead to non-spherical geometry. For instance, Matt et al. (2000) have shown that a dipole field could create a dense equatorial torus and collimate the winds (with no need of a companion star). The newly created aspherical geometry would then be conserved and/or enhanced with the evolution towards a toroidal field.

Taking into account all the recent works arguing for the major role played by close binary systems in the shaping of PPNe/PNe (e.g. Soker 2004; Nordhaus 2008; Douchin et al. 2013; Tocknell et al. 2013), a plausible scheme would involve a rotational effect induced by binary interaction which then would have some dynamical effects on the formation and evolution of the magnetic field and on the objects’ morphologies.

4.4.1 Molecular outflows and launching mechanism

The study of the emission lines in both PPNe can help us to investigate the relationship between the outflows and the magnetic field. In both objects we note the relatively strong and high velocity of the CO outflows and as the $^{12}$CO(J=3$\rightarrow$2) line is the most significant in terms of intensity we will then consider that the molecular outflows are mainly supported by this emission line. Fig.4 and Fig.6 Top show the CO molecular outflows for CRL 618 while Fig.5 and Fig.6 Bottom show the same but for OH 231.8+4.2.

A good positional correlation between the continuum area and
the $^{12}$CO emission in CRL 618 is seen in Fig. 4. The comparison of the direction of the well organised magnetic field vectors with that of the overall CO molecular outflows in Fig. 7-Left, shows that they are well aligned.

Concerning OH 231.8+4.2, Fig. 5 indicates a slight misalignment of the continuum area with respect to the $^{12}$CO emission distribution of $\sim 30^\circ$. Fig. 7-Right shows that the X-shaped (or pinched waist) structure of the magnetic field in OH 231.8+4.2, mostly the northern and eastern segments, encompasses quite well the blue and red-shifted lobes of the $^{12}$CO emission. The magnetic vectors in OH 231.8+4.2 are globally parallel to the CO molecular distribution and trace quite well the outer contours of the red- and blue-shifted CO lobes.

In both cases the alignment between the major axis of the molecular outflows and the ordered magnetic field vectors suggests not only a dynamically important field at small scale but could also indicate the presence of a magnetic launching mechanism of these outflows. Our observations are concordant with the theoretical predictions by Blackman et al. (2001) relative to the presence of a poloidal geometry of the magnetic field at small distance from the central star and its role in the launching of the flows in proto Planetary Nebulae. Recently, Pérez-Sánchez et al. (2013) have also reported the radio observation of a magnetically collimated outflow/jet shaping the post-AGB star IRAS 15445-5449. However we cannot discard the possibility of a field dragged by the powerful outflows, particularly in the case of OH 231.8+4.2. Investigations at larger depths, i.e. closer to the central star, are however needed to fully assert the hypothesis outflow launching theory.

### 4.5 Magnetic field strength

Chandrasekhar & Fermi (1953) described a method to derive the magnetic field strength based on the dispersion of the polarisation angles, the gas density and rms velocity.

$$B_{\text{POS}} = \sqrt{4\pi \rho \sigma_V / \sigma_\phi}$$  \hspace{1cm} (1)

This method has been widely used to estimate the field strength in molecular clouds and star forming regions and has been adjusted over time to give a more accurate representation of this field (Ostriker et al. 2001; Falceta-Gonçalves et al. 2008; Koch et al. 2012). However as it stands the CF method can hardly be applied to our evolved nebulae. The method is based on the assumption that the magnetic field dispersion is Alfvénic but its application in a non-quiescent environment i.e. where turbulences/perturbations occur is problematic. Indeed, although our nebulae could show signs of locally dominant Alfvén waves' con-
distribution (Sabin, Zijlstra & Greaves [2007]), they are subject to ionisation and collision processes among other turbulent phenomena, which are likely to alter the vector polarisations and then the PA dispersion. In conclusion the CF method in its actual form is not adapted to account for the magnetic field strength in our type of nebular media.

An estimate of the field strength can however be obtained via maser observations and Zeeman splitting analysis. Table I summarises the different studies using this method related to CRL 618 and OH 231.8+4.2. It is worth mentioning that these masers are located in the outer layers of the envelopes and are therefore not very reliable for a global field estimation.

By determining the ratio $\beta$ between the thermal pressure $P_{th} = n_{th} k T$ and the magnetic pressure $P_{B} = B^{2}/8\pi$ we can estimate the lower limit on the magnetic field’s strength for which the field would become dominant. Bujarrabal et al. [2002] provided a detailed analysis of OH 231.8+4.2 and its physical conditions and following their work we calculate that in the dense central part of the PPN where $T = 35 K$ and $n_{th} = 3 \times 10^{15} cm^{-3}$, the magnetic pressure dominates for $B \gtrsim 0.6 mG$. This threshold indicates that, assuming Leal-Ferreira et al. [2013]'s result, the magnetic pressure largely dominates the thermal pressure at this location in this PPN.

Similarly, based on the work by Sánchez Contreras et al. [2004] in the dense core of CRL 618 ($T = 55 K$ and $n_{th} = 7.5 \times 10^{15} cm^{-3}$), the magnetic pressure dominates for $B \gtrsim 1.2 mG$, a value much lower than that found by Herpin et al. [2009]. Although we estimated upper limits on the magnetic field for the molecular (neutral) areas in both PNes (with low temperatures and high densities), the ionised regions (with higher temperatures) should not be discarded as the field still needs a partial ionisation to connect to the gas. Indeed in the outflows (showing high kinetic energy), the magnetic field might not govern the gas flow. We are therefore likely to see a variation of the field-flow relation inside the PPN.

5 CONCLUSIONS

In this paper we present high resolution SMA submillimeter polarimetric observations of the proto-planetary nebulae CRL 618 and OH 231.8+4.2. In both cases we detected linear polarisation $\sim 3\sigma$ and a higher percentage polarisation is found in CRL 618 (C-rich) compared to OH 231.8+4.2 (O-rich). The difference is likely to be linked to the chemical nature (i.e. dust grain type) of the PNes as also reported by Sabin, Zijlstra & Greaves [2007] for other evolved objects.

Also, the polarisation vectors indicate that the resulting magnetic field geometry supports the presence of a clear and well organised poloidal magnetic structure (i.e. aligned with the pairs of ionised outflows) in both PNes. But while this configuration is more ‘simple’ in CRL 618; the field shows an X-shaped structure in OH 231.8+4.2 and appears particularly patchy (although the field is organised in each individual component). However we do not discard the possibility that some vectors might belong to a toroidal field.

The observation of polarisation in the molecular lines, and particularly the CO lines, led to no positive detections above $3\sigma$ in any of the PN but we clearly observed, in both cases, an alignment of the ionised and molecular outflows with the magnetic field vectors, at large and small scales respectively, which supports the idea of a dynamically important field at small scale and of a probable magnetic launching origin for these outflows.

Finally we present a tentative explanation for the field’s configuration evolution in late type stellar objects.

The SMA proved to be an excellent tool to study the polarisation and magnetic field distribution in evolved stars. A better understanding of the role and evolution of magnetic fields in the late stages of stellar evolution will require more of these submillimeter and millimeter observations to investigate any evolutionary scheme or magnetic launching mechanism. In the future with the more sensitive polarisation capabilities of ALMA, we will be able to target a larger range of evolved objects particularly the faint PNes and PNe.

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