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Letter to the Editor

Toroidal magnetic fields around planetary nebulae

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Abstract. Many planetary nebulae have asymmetric winds, often forming bipolar outflow lobes or jets. One theory for this phenomenon is that differential rotation of the envelope twists the star's magnetic field into a toroidal flux tube, which channels the fast winds. Direct testing of this theory is now possible using submillimetre polarimetry of magnetically aligned dust grains, and such a test has been made for the planetary nebula NGC 7027 and the proto-planetary nebula CRL 2688. The results show that the magnetic field is within 15 degrees of toroidal towards NGC 7027, but about 35 degrees off-axis for CRL 2688. However, the telescope beam size of 15″ is well matched to the size of the jet base in NGC 7027 and poorly so in CRL 2688 where the observation is more sensitive to the extended envelope. Magnetic field directions in the envelopes are not well aligned with the outflow axes. The polarization percentage is an order of magnitude less towards NGC 7027 than in the outer envelope, so assuming similar grain alignment efficiencies everywhere, the scale of the organised toroidal field is of the order of 5000 AU.

Key words. magnetic fields – stars: AGB and post-AGB – planetary nebulae: individual: CRL 2688 – planetary nebulae: individual: NGC 7027

1. Introduction

The slow winds from asymptotic-giant branch (AGB) stars generally produce spherically symmetric circumstellar emission (e.g. Josselin et al. 2000), while the more evolved proto-planetary nebulae and planetary nebulae (PPN, PN) often have fast winds forming complex structures. These include bipolar outflow lobes, narrow jets, and sometimes multiple shells and lobes. There are three general classes of model to explain this large change in the symmetry over a short transition time (less than $\sim 10^3$ years; Stanghellini & Renzini 2000). An overview has been presented by García-Segura et al. (1999). Firstly, a low-mass companion star could exert a gravitational pull on the circumstellar envelope, creating a non-spherical density distribution that channels the wind into two opposite directions. Secondly, with rapid rotation, conservation of angular momentum tends to create a denser layer around the stellar mid-plane, producing a similar gradient effect. Thirdly, magnetic forces could be involved: magnetic fields emerging from the stellar surface may become wrapped up by differential rotation into a "tube". The later, post-AGB, fast winds will then be collimated into two lobes, and this has been seen in simulations (García-Segura et al. 1999). A dynamo action between the rapidly rotating star and more slowly rotating envelope has recently been suggested as the origin of the field (Blackman et al. 2001).

It is now possible to test the magnetic collimation hypothesis observationally. The technique of submillimetre imaging polarimetry has recently been developed (Dowell et al. 1998; Greaves et al. 2002) and this provides a direct probe of magnetic field directions in sources with thermal dust emission. Magnetic relaxation tends to align any elongated grains so that they spin with their long axes perpendicular to the local field, and this becomes the direction of preferential linear polarization. Thus, a map of the perpendiculars to the p-vectors gives a direct image of the magnetic field (as projected onto the plane of the sky). The disadvantage of this technique is that angular resolution is poor with single-dish telescopes: on the 15 m James Clerk Maxwell Telescope (JCMT), the beam size is 15″ for imaging polarimetry at 850 μm wavelength. Therefore, two relatively nearby sources were chosen for the initial observations: the PN NGC 7027 and the PPN CRL 2688, both at about 800 pc distance. Each of these has dust emission extending over about 10″ (at half-maximum intensity), and the jets of CRL2688 are clearly seen out to 30–40″ from the star.

2. Observations

The data were obtained on 2000 October 7 and 10 (UT), with the UK/Japan Polarimeter on the Submillimetre Common-User Bolometer Array (SCUBA) at the JCMT. Integration times were approximately 1.5 hours per source, in moderately good weather with zenith opacities at 850 μm of around 0.32. CRL 2688 is a standard calibrator with a total flux of 6.4 ± 0.5 Jy and was used to establish the flux scale for both sources (Jenness et al. 2002). Polarization detections were obtained for regions brighter than 600 mJy, with a noise level of about 5–10 mJy.

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The standard “jiggle-map” observing mode was used (Holland et al. 1999), with the secondary mirror chopping over ±120″ on the sky to set the zero level, plus sky noise removal using the outer of the three rings of bolometers (Jenness et al. 2002 and references therein). Polarimetry was done in the standard mode, by taking a series of images with the rotating half-wave plate at angles of 0, 22.5, 45... 337.5°; the signal seen by the bolometers through a linearly-polarizing grid then has a sinusoidal modulation. The observing and data reduction procedures have been described by Greaves et al. (2002). The polarimetry data were sampled every 6″ on the sky and have been binned over 15″ square regions, the same width as the half-maximum beam diameter. Each vector plotted is therefore largely independent, although sampling beams unavoidably share overlapping flux regions on the sky. A polarization standard was taken on the first night using the radio flux peak of the Crab Nebula observed by Flett & Murray (1991); the position angle difference compared to the standard was ∼3° (less than the errors).

2.1. Subtraction of instrumental polarization

Instrumental polarization (IP) arises from the JCMT’s woven “windblind” and at the mirrors between the tertiary and SCUBA. By default, the main-beam IP is subtracted using a database of values measured for each bolometer, using planets that are assumed to be unpolarized (Greaves et al. 2002). For the central bolometer, which observed the flux peak in three-quarters of our data, the IP has been very accurately measured. On 2000 October 10, the measured IP on Saturn was 0.99 ± 0.12% at 161 ± 4°. However, Saturn’s rings may be slightly polarized so the value adopted was from eight months of observations of Mars and Uranus (late 2000 to early 2001), with a mean value of 1.01 ± 0.11% at 166 ± 3°.

Off-axis optical effects can also produce “sidelobe” IP of about 2–5%. This is a problem when observing the outflows, because the main nebula is bright and lies to one side of the telescope beam. The exact effects depend on the sidelobe amplitude, relative fluxes, and instrumental polarization pattern, but a rejection threshold can be established (Greaves et al. 2002). For NGC 7027 and CRL 2688, the criterion used was that the polarized flux entering through the sidelobe should be less than half the polarized flux of the target region. The result was that off-centre polarizations of more than ≈1.2% will have systematic position angle errors of less than 15 degrees, and only points meeting this criterion are plotted. The converse effect, of off-centre points contaminating the central measurement, results in an error of ∼6°.

3. Results

The magnetic field directions[1] are plotted in Figs. 1 and 2, with vectors of length proportional to the percentage polarization

Table 1. Details of the polarization measurements. Co-ordinates are arcsecond offsets and p, θ are the degree and direction of linear polarization. All data are for 15″-square regions. For other points offset by 15″ from the stars, the measured percentages were 0.7 to 1.1% and were rejected due to sidelobe contamination (see text).

source	offset	flux (Jy)	p (%)	θ (degrees)
NGC 7027	(0, 0)	3.2	0.28 ± 0.08	−52 ± 8
	(0, −15)	0.6	1.8 ± 0.3	+28 ± 5
	(+15, 0)	0.6	1.4 ± 0.3	+78 ± 7
CRL 2688	(0, 0)	2.5	0.26 ± 0.08	+53 ± 9
	(0, −15)	0.7	1.9 ± 0.4	−7 ± 5
	(−15, 0)	0.7	4.7 ± 0.4	+46 ± 2
	(0, +15)	0.8	2.2 ± 0.3	+71 ± 4

(Table 1). The percentage is not a measure of magnetic field strength, but relative values provide some information on the degree of order in the field structure. The direction is a direct diagnostic of the mean magnetic field orientation within the telescope beam.

For NGC 7027, the magnetic field towards the centre is consistent with toroidal, being oriented across the jet directions. These outflows are at position angles of approximately −65° and −30° (Latter et al. 2000), so the mean direction of −48° is very closely aligned with the polarization angle of −52 ± 8°. This means that the magnetic field is aligned with the inferred major axis of the torus.

For CRL 2688, the jets have position angles of 10° and 25°, not well aligned with the polarization direction of 53 ± 9°. The field is about 35 degrees off the toroidal direction, but still closer to this than the polar axis. It is likely that the telescope beam is more sensitive to the envelope as a whole than the region at the base of the jets where any toroidal field would presumably be located. The jet base is about 2″ in the NICMOS images (Sahai et al. 1998), while the JCMT beam is 15″ in diameter. For comparison, NGC 7027 is much better matched to the beam, with the broad outflow lobes being 8–9″ across at the base (Latter et al. 2000).

Only a few polarization vectors were detected away from the flux peaks, and above the 1.2% criterion established earlier. The vectors in the extended envelopes lie at ≈30–70° to the nearest jet axis. This effect is surprising, since a misaligned magnetic field will tend to deflect the outflow (e.g. Hurka et al. 1999). More data points are needed to establish the true geometries, but the few points obtained already rule out both completely radial or completely toroidal magnetic fields on scales of the entire circumstellar envelope.

3.1. Systematic errors

Since the central polarization percentages are very small, around 0.3%, systematic errors need to be considered. The signal-to-noise ratios are 3.25 and 3.5, associated with a >99% confidence levels (Simmons & Stewart 1985) and the position angles are nominally established to a rather accurate 8–9°.

[1] The normal assumption is made that the observed E-plane of polarization is perpendicular to the magnetic field. Effects such as grain alignment by gas molecules streaming past (Lazarian 1997) are ignored.

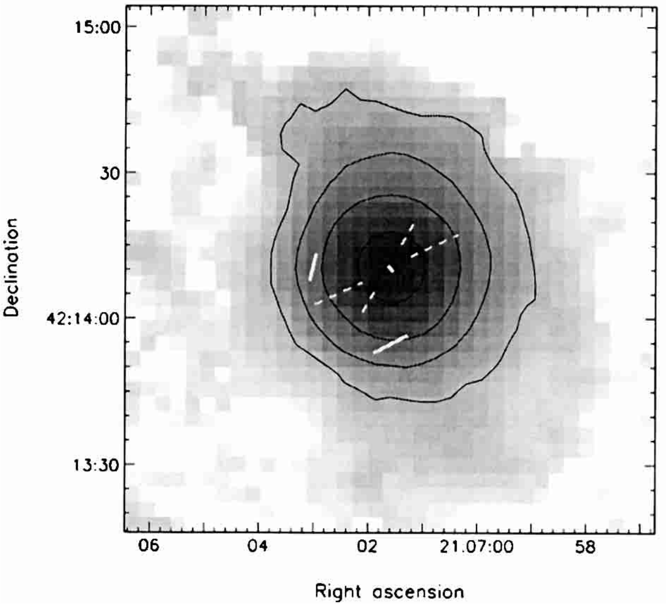

Fig. 1. Polarization results for NGC 7027. The vectors show the 850 μm magnetic field directions (rotated 90° from the observed polarization directions), superimposed on the 850 μm intensity on a base-10 logarithmic scale from 0.03 to 30 mJy/arcsec^2 (white to black). The contours are 0.3, 1, 3 and 10 mJy/arcsec^2 and the scale of the vectors is from 0.3 to 1.8%. The dashed lines show the inferred outflow axes within the broad lobes (Latter et al. 2000). Co-ordinates are given in the J2000 system, and the pixel size is 3.1″.

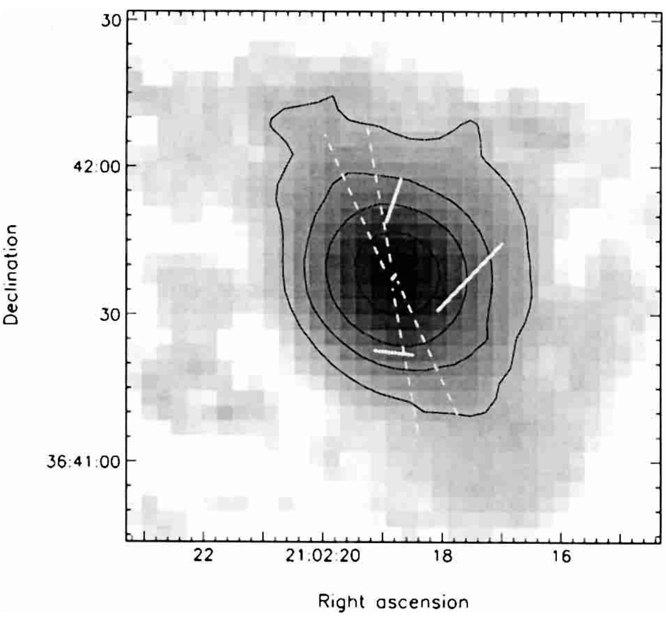

Fig. 2. As for Fig. 1, but for CRL 2688. The vectors range from 0.3 to 4.7%, and the dashed white lines show the approximate scale and orientation of the jets as observed by NICMOS (Sahai et al. 1998).

However, the main-beam instrumental polarization discussed earlier has a measurement error of 0.1%, which could enter as a systematic offset fixed in the instrument co-ordinate frame. This was assessed by introducing this systematic and tracking the change in the source p, θ over the parallactic angles of the actual observations (150–105° for CRL 2688 and 125–90° for NGC 7027). The results showed that the worst cases are an absolute position angle shift of 10°. Adding this in quadrature with the sidelobe-IP systematic and the statistical error, the total angle uncertainties are $\leq$15°. Thus the conclusion that the NGC 7027 magnetic field is close to toroidal is not seriously affected by the systematics.

4. Discussion

The NGC 7027 result is the first direct evidence of a toroidal-shaped magnetic field towards a bipolar planetary nebula, and suggests that the magnetic collimation mechanism can indeed work. The magnetic orientation for the less-evolved PPN CRL 2688 is unclear, and it is probable that the beam is dominated by the emission from the extended envelope rather than any toroid region. Cox et al. (2000) have found evidence for multiple flows over the last ~1200 years, lying in four different directions within a 15″ region. This complex evolution would be likely to perturb the magnetic field structure.

Without measurements of the field strengths, magnetic collimation models can only be tested by the geometry, but in NGC 7027 this agrees with predictions. Previously, Miranda et al. (2001) detected a magnetized torus approximately 600 AU in radius around the PN K3-35, with an inferred milli-Gauss strength field, but the technique of measuring Zeeman circular polarization did not constrain the orientation of the magnetic field. Together the results support a magnetised torus that can direct the outflow. In the torus models of García-Segura & Lopez (2000), the stellar field is a few Gauss and with an r^{-1} decline of the toroidal component, a few milli-Gauss would be expected at hundreds of AU (if the stellar field lies at a radius ~100 $R_\odot$). In contrast, models invoking a dipolar field (Matt et al. 2000) decline too steeply, as r^{-3}, and produce a large-scale radial field that is not seen here.

Other proposed models for producing bipolar winds invoke the gravitational effects of rapid rotation in the stellar mid-plane or of a companion star. García-Segura & Lopez (2000) have modelled PN winds with and without magnetic fields, and found that with rotation alone, there is insufficient wind convergence to produce narrow jets. This leaves the companion class of models as the main alternative mechanism. NGC 7027 has no known companion (Ciardullo et al. 1999), while CRL 2688 does have a companion candidate (Sahai et al. 1998). However, Weintraub et al. (2000) argue that this object is too distant, at approximately 1000 AU, to produce any collimating effect on the outflow gas.

4.1. Extended polarization and magnetic scales

The mean value of the off-centre polarization is ≈2.5%, whereas the degree of polarization towards the central stars is an order of magnitude less. Several effects can reduce the percentage: a change in inclination (but this should be a global quantity for the whole nebula); poor grain alignment; or small-scale magnetic field structure producing polarization directions that cancel within the telescope beam.

Grain alignment efficiency depends on the composition, shape and size of the dust particles and on the local gas density. The grain properties should be rather constant, as suggested by similar submillimetre spectral indices across the nebulae. Sánchez Contreras et al. (1998) have mapped both sources at 1300 μm, and combining their 12″ resolution data with the JCMT 850 μm maps, the (1300:850) flux ratio is 0.36 and 0.30 inside and outside the main beam towards NGC 7027, respectively. This is rather constant, as the the two corresponding values of 0.18 and ~0.11 for CRL 2688. The grain properties therefore appear to be independent of radius. Frequent collisions in dense gas could misalign grains, but the typical densities will only be a few 10^5 H_2 molecules cm^{-3}, assuming envelope masses around one solar mass and radii of about 5″. This is less than in protostellar envelopes, for example, which are often polarized at the several percent level in the submillimetre (e.g. Davis et al. 2000).

Thus, the remaining reason for reduced polarization percentages is a change of magnetic field geometry within the central beam compared to the outer envelope. A simple general hypothesis is that the magnetic field is ordered over beam size scales in the outer envelope, but more complex at the centre of the nebula. Then comparing the polarization percentages gives an effective size scale for the "organised" magnetic torus within the central beam. The factor of six decrease for NGC 7027 suggests that the torus occupies 1/6th of the beam area, or about 40% of the diameter. This 6″ size corresponds to 5000 AU at the ~800 pc distance to the nebula. This is a surprisingly large scale compared to the stellar radius but is broad agreement with the 8–9″ diameter of the base of the jet system.

5. Conclusions

A toroidal magnetic field has been detected around NGC 7027, with an effective scale of ~5000 AU. This field is correctly oriented to collimate the observed bipolar winds, and of a dimension similar to the base of the outflow. Magnetic collimation is thus a viable alternative to models invoking gravitational disturbances by companion stars, which are rarely detected by direct observation (Phillips 2000).

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