Asymmetric Planetary Nebulae III
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M. Meixner, J. Kastner, B. Balick and N. Soker eds.

Indra Bains, Timothy Gledhill

Department of Physics, Astronomy & Maths, University of Hertfordshire, College Lane, Hatfield, Hertfordshire, AL10 9AB, U.K.

Anita Richards

Jodrell Bank Observatory, Department of Physics and Astronomy, University of Manchester, Macclesfield, Cheshire, SK11 9DL, U.K.

Jeremy Yates

Department of Physics and Astronomy, University College London, Gower Street, London, WC1E 6BT, U.K.

Abstract. Our understanding of the morphological evolutionary path from AGB star to planetary nebula is still unclear; broadly speaking, we are faced with shaping models that primarily detail varying forms of binary evolution, and those which concentrate on the influence of stellar magnetic fields. Here we report the detection and measurement of a magnetic field in the proto-planetary nebula IRAS 20406+2953. This is the second such object in which we have measured a field strength and shown that the magnetic energy density in the wind is an order of magnitude higher than the bulk mechanical energy density, suggesting that the magnetic field could be influential in shaping the outflow.

1. Introduction

Observational results (e.g. Manchado et al 2000) suggest that $\sim$ 50–80 per cent of planetary nebulae (PN) are elliptical or bipolar, that is, they display *axisymmetry*. Additionally, the PN structures are sometimes further complicated by the presence of point-symmetric knots, high-velocity outflows and multipolar bubbles (e.g. the case of MyCn 18; Bryce, Bains, López & Redman, these proceedings). Within the currently-accepted framework of late-type stellar evolution, this means that stars that are spherical whilst on the Asymptotic Giant Branch (AGB) have to evolve in a manner that can produce the complex morphologies observed in PN. The most intriguing questions in stellar research regard the nature of this morphological evolution: what causes it, and at what stage in stellar evolution does it take effect?

Some of the most promising current models that detail stellar evolution in the AGB to PN phases and can produce the complex structures seen in the evolved objects, invoke the potential role played by magnetic fields (e.g. see Matt, Frank & Blackman in these proceedings and Blackman, also in these proceedings). With the aim of testing the models, detecting the predicted fields and interpreting their structures (in particular, are they poloidal or toroidal?), we have a programme of MERLIN full polarization, spectral line, radio observations of the circumstellar (CS) OH masers in a sample of proto-planetary nebulae (PPN). Any polarization structure detected is interpreted as being due to Zeeman splitting by the local stellar magnetic field. These observations provide a spatial resolution of ~ 2 arcsec and a velocity resolution of ~ 0.35 km s^{-1}. We reported the first measurement of a magnetic field strength in a PPN, OH17.7–2.0, in Bains, Gledhill, Yates & Richards (2003). In these proceedings, we present the results from our MERLIN maser observations of the PPN IRAS 20406+2953.

2. Results & Discussion

The regular, twin-peaked OH Stokes I velocity profile observed at 1612 MHz (Fig. 1) suggests that the masers lie in a shell structure that is expanding at a constant velocity (e.g. Cohen 1989). Polarization structure is seen across the full velocity range of the emission at this frequency. At 1667 MHz, the Stokes I velocity profile (not shown) is irregular and 40 times fainter than the emission seen at 1612 MHz, possibly the reason that no polarization was detected at the former frequency. The rest of our discussion is restricted to the 1612 MHz data as this gives much more information than that provided by the little emission detected at 1667 MHz. The data cube channel maps and the spatial distribution of the maser features (Fig. 2a) seen at 1612 MHz again suggest a shell-like structure for the emission, but with the NE and SW 'caps' missing so that the strucure appears more as a torus, with its equatorial axis inclined at $\sim 120°$ in the plane of the sky. A least-squares programme was used to fit to the centre of expansion of the masers to produce a viable stellar position; this was found to be between features 01 and 19 in Fig 2a, along the line-of-sight. Two-dimensional plots of the angular separation of the maser components from this stellar position, versus their velocity, reveal again that most of the 1612 MHz emission exists in a shell-like structure, with some outlying components possibly involved in a bipolar interaction such as that suggested by the models of Zijlstra et al. (2001).

If it is assumed that it is the σ-components of the Zeeman pattern that are observed in the polarization data, then in the plane of the sky, the linear polarization vectors are perpendicular to the magnetic field direction. Linear polarization was detected at 1612 MHz (Fig. 2b) mainly in the two peak Stokes I features, numbered 01 and 19 in Fig. 2a, that are also almost aligned along the line-of-sight. The flux-weighted mean polarization angle of the redshifted feature is 71° and that of the blueshifted feature is 57°, giving magnetic field directions in the plane of the sky of 161° and 147° respectively. Note that we have not yet considered the effect of potential internal Faraday rotation. These field directions on the near and far sides of the PPN 'shell', coupled with the structure suggested by the 1612 MHz Stokes I masers of a toroidal shell inclined at 120° in the plane of the sky, suggest a field structure that is more toroidal than poloidal.

The resolved Zeeman split detected in the 1612 MHz Stokes V data give a field strength of -3.1 mG. This was measured in feature number 19 in Fig.

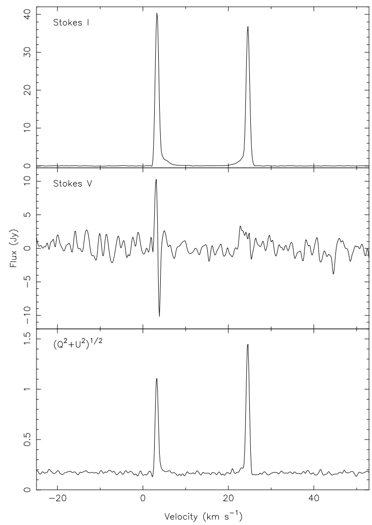

Figure 1. The 1612 MHz OH velocity profiles of the Stokes parameters.

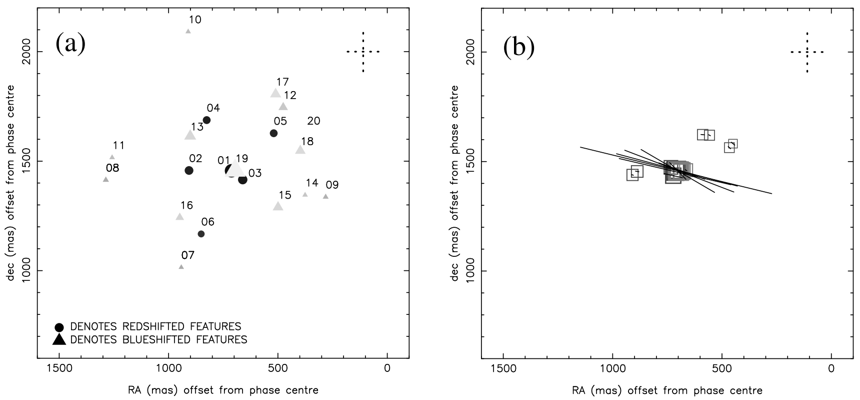

Figure 2. Spatial distribution of the 1612 MHz (a) total intensity (Stokes I) maser features and (b) linearly polarized maser components, plotted relative to the observing phase centre. In (a) symbol size is proportional to the logarithm of peak flux in the feature and in (b) symbol size is proportional to the logarithm of the component total (Stokes I) flux density; vector magnitude (1 arcsec $\approx$ 890 mJy beam^{-1}) is proportional to the component linearly polarized flux density. Feature 20 is the most blueshifted and 01 is the most redshifted. The fitted stellar position lies between the 2 peak features, 01 and 19, along the line-of-sight. Lighter grey symbols represent more blueshifted emission and darker grey more redshifted. The dotted cross indicates the restoring beamsize.

2a. If it is assumed that the distance to IRAS 20406+2953 is 1 kpc, then this field strength is measured $\sim$ 500 au from the star. Calculations of the magnetic and bulk mechanical energy densities in the stellar wind show that the magnetic energy density is an order of magnitude higher, suggesting that it is influential in the shaping of the outflow.

3. Conclusions

This is the second PPN in which we have detected a magnetic field, mapped the polarization structure and measured the field strength. In both of these objects, we have shown that the energy contained in the field is sufficient to influence the outflowing wind. We note that Soker & Kastner (2003) and references therein, suggest that magnetic flares can produce locally-strong magnetic fields in 'magnetic clouds' and that it is these that are sampled by maser polarization observations. This would mean that the magnetic field played a secondary role; instead of being a dynamic influence on a global scale its influence would possibly be in enhancing localised dust formation. However, the results presented in this paper illustrate that PPN have significant field strengths, if only localised, and therefore the magnetic field models need more observational verification. It is likely that in reality, some combination of factors e.g. magnetic fields, disks, binarity and rotation act to produce the morphological diversity of PN.

4. Acknowledgements

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