AAOmega radial velocities rule out current membership of the planetary nebula NGC 2438 in the open cluster M46

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ABSTRACT

We present new radial velocity measurements of 586 stars in a one-degree field centred on the open cluster M46, and the planetary nebula NGC 2438 located within a nuclear radius of the cluster. The data are based on medium-resolution optical and near-infrared spectra taken with the AAOmega spectrograph on the Anglo-Australian Telescope. We find a velocity difference of about 30 km s⁻¹ between the cluster and nebula, thus removing all ambiguities about the cluster membership of the planetary nebula caused by contradicting results in the literature. The line-of-sight velocity dispersion of the cluster is 3.9 ± 0.3 km s⁻¹, likely to be affected by a significant population of binary stars.

Key words: planetary nebulae: general – open clusters and associations: general.

1 INTRODUCTION

Any physical associations discovered between planetary nebulae (PNe), the short lived but spectacular late evolutionary stage of small and intermediate mass stars (between 1 and 8 M☉), and star clusters would be a valuable discovery that provides a means of establishing accurate astrophysical parameters for the nebulae through fixing distances and progenitor ages from cluster isochrones. Accurate distances are particularly useful, from which one can infer PNe physical properties such as the absolute magnitude of the central stars, accurate physical dimensions and fluxes. Also, they would provide excellent calibrators for the surface brightness–radius (SB–r) relation (Frew & Parker 2006; Frew 2008). Whereas PNe have been found in four globular clusters of the Milky Way (M15, M22, Pal 6 and NGC 6441; Jacoby et al. 1997), none has been reported in the literature as an unambiguous member of a much younger open cluster (OC). The interest in the latter case is not only due to being a true OC–PN association. A compelling case in an old OC that may prove the best candidate yet for a true OC–PN association.

NGC 2438 is a well-known annular PN located about 8 arcmin from the core of the bright OC M46 (=NGC 2437; BBS08). Despite its brightness, the cluster was relatively unstudied until recently (e.g. Cuffey 1941; Stetson 1981). Recently published cluster parameters are relatively well determined, e.g. E(B − V) = 0.10–0.15, D = 1.5–1.7 kpc and an age of 220–250 Myr (Sharma et al. 2006; MTL07; BBS08). The estimated turnoff mass is about 3.5 M☉ (BBS08). In addition to the possible association with NGC 2438, M46 is also thought to host the well-studied post-asymptotic giant branch candidate OH 231.8+4.2 (Jura & Morris 1985).
Early studies of the radial velocity of NGC 2438 and M46 (Cuffey 1941; O’Dell 1963) indicated a difference of \( \Delta v_r \approx 30 \text{ km s}^{-1} \) between the PN and cluster stars, which suggested that the pair constitutes a spatial coincidence only. Three red giants in the cluster have systemic velocities (Mermilliod et al. 1989, 2007) identical to that of cluster dwarf members obtained by Cuffey (1941). However, Pauls & Kohoutek (1996) rekindled interest in the possibility of the PN/OC association when they found similar velocities for both, although based on a small number of stars. Both MTL07 and BBS08 pointed out the importance of measuring sufficient stellar radial velocities for the cluster and PN to establish if the proximity is real or only chance superposition.

Previous distance estimates to the cluster and PN gave similar results though the distance estimates to the OC are far more accurate than the crude statistical estimates for the PN distance provided by Zhang (1995). A distance can be estimated based on the H\(\alpha\) SB–\(r\) relation observed for PNe (e.g. Frew & Parker 2006; Frew 2008). Using an updated version of the relation first presented in Pierce et al. (2004), a distance of 1.4 \pm 0.4 kpc is estimated. Using instead the relation applicable to bipolar and bipolar core PNe (Frew, Parker & Russell 2006), \( D = 1.9 \pm 0.5 \text{ kpc} \). These values are in broad agreement with other recent SB–\(r\) determinations in the radio domain, e.g. Van de Steene & Zijlstra (1995), \( D = 1.7 \text{ kpc} \), Zhang (1995), \( D = 2.1 \text{ kpc} \), Phillips (2004), \( D = 1.2 \text{ kpc} \) and Stanghellini, Shaw & Villaver (2008), \( D = 1.2 \text{ kpc} \), and are all compatible with the cluster distances (MTL07, BBS08).

Because of the recently revived interest in possible OC–PN associations, we obtained new multi-object spectroscopic observations of M46 and NGC 2438, where a putative association has still not been satisfactorily resolved due to ambiguities and confusion in the literature. Here, we present a statistically significant radial velocity sample of 586 stars within 0.5 of the cluster centre. The data leave no doubt that the PN is not a member of the cluster.

## 2 Observations and Data Reduction

We used the AAOmega double-beam spectrograph on the Anglo-Australian Telescope in Siding Spring, Australia on 2008 February 17. The seeing on that night was about 1.5–2 arcsec. In the blue arm, we used the 2500V grating, providing \( \lambda / \Delta \lambda = 8000 \) spectra between 4800 and 5150 Å. These were important for measuring the mean and expansion velocities of the PN from the H\(\beta\) and [O\(\text{iii}\)] lines. In the red arm, we used the 1700D grating that has been optimized for recording the Ca\(\text{ii}\) IR triplet region. These spectra range from 8350 to 8790 Å, with \( \lambda / \Delta \lambda = 10,000 \). This setup has the highest spectral resolution available with AAOmega and hence the red spectra were used to measure stellar radial velocities.

In total, we acquired two field configurations centred on the OC. The target stars were selected from the Two-Micron All-Sky Survey (2MASS) point source catalogue (Skrutskie et al. 2006) by matching the main features in the colour–magnitude diagram of stars within the central 5 arcmin. The total field of view was 1° across. We estimated V- and I-band magnitudes from the 2MASS \( JHK \) magnitudes using the same set of linear transformations as in Kiss et al. (2007).

The full magnitude range of the target stars in \( V \) was from 10 to 15 mag, but for a single configuration we limited the brightness range to 3 mag in order to avoid cross talk between the fibres due to scattered light. The log of observations is presented in Table 1. Fig. 1 shows the sky positions of the observed stars, while Fig. 2 depicts the three fibre positions across the face of the PN (because of the limitations of fibre-to-fibre proximity, the central star was in the first configuration, the northern and southern rim positions were in the second configuration). The upper panel of this figure is based on Spitzer/IRAC (Infrared Array Camera) observations of NGC 2438 obtained from the Spitzer archive (Prog. ID: 68, ‘Studying Stellar Ejecta on the large scale using SIRTF-IRAC’, PI: G. Fazio). We downloaded the frames processed with the SSC IRAC Pipeline v14.0, and mosaics were created from the basic calibrated data (BCD) frames using a custom \texttt{IDL} program. For details, see Gutermuth et al. (2008). As a comparison, the lower panel in Fig. 2 shows a deep \( H\alpha \) image (Parker et al. 2005), indicating that the Spitzer-based positions did indeed coincide with strong optical emission.

The spectra were reduced using the standard 2dF data reduction pipeline. We performed continuum normalization separately for the stellar spectra using the \texttt{IRAF} task \texttt{onedspec.continuum} and then cleaned the strongest skylines that had residuals left using linear interpolation of the surrounding continuum. The nebular spectra were extracted in instrumental fluxes only.

## 3 Analysis

### 3.1 Stellar Spectra and Velocities

Atmospheric parameters and radial velocity were determined for each star with an iterative process, which combined finding best-fitting synthetic spectrum from the Munari et al. (2005) spectrum library, with \( \chi^2 \) fitting, and cross-correlating the best-fitting model with the observed spectrum to calculate the radial velocity. This

Table 1. Log of observations.

<table>
<thead>
<tr>
<th>Field</th>
<th>Exposure time (min)</th>
<th>Mid-point HJD</th>
<th>Cluster</th>
<th>PN</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40</td>
<td>2454513.918</td>
<td>282</td>
<td>N/S rim</td>
</tr>
<tr>
<td>2</td>
<td>65</td>
<td>2454513.957</td>
<td>304</td>
<td>Central star</td>
</tr>
</tbody>
</table>

Figure 1. Sky positions of the stars observed with AAOmega.
Current membership of NGC 2438 in M46 ruled out

Figure 2. Spitzer/IRAC (upper panel) and SuperCOSMOS Hα (lower panel) images of NGC 2438. The white squares show the three fibre positions we used to take spectra of the PN. North is up, east is to the left-hand side, the field of view is 6 arcmin.

3.2 PN spectra and velocities

The spectra taken in the three positions across the PN depicted in Fig. 2 are typical of a PN. The blue range shows the three characteristic nebular emission lines, the Hβ and the [O III] doublet at 4959 and 5007 Å, which are far the strongest features in the optical spectrum. The central spectrum shows well-defined double-peaked [O III] line profiles (upper panel of Fig. 4), which we used to determine the expansion velocity of the nebula, assuming a spherical shell. The two spectra on the edge have single-peaked emissions, centred exactly halfway between the two peaks of the central spectrum, supporting that assumption.

In the near-IR, the central position yielded a featureless flat continuum, while the two spectra from the shell contain an identical set of narrow emission lines (lower panel in Fig. 4). Using line identifications from the literature (Aller 1977; Rudy et al. 2001) and the NIST atomic data base (Ralchenko, Kramida & Reader 2008), we identified the detected lines as the Paschen series of hydrogen (from P12 to P18), the [Cl II] nebular line at 8579 Å and the N I line at 8729 Å.
Individual radial velocities have been measured by fitting Gaussian functions to the line profiles. In case of the double-peaked [O III] doublet, we fitted a sum of two Gaussians. In each case, we repeated the centroid measurement by choosing slightly different fit boundaries to estimate the uncertainty: the strong emission lines in the blue yielded the same velocities within 1–2 km s\(^{-1}\) in several repeats, while the weak Paschen lines in the low signal-to-noise ratio (S/N) near-IR spectra were more sensitive to the actual choice of fitting limits, resulting in up to 3–5 km s\(^{-1}\) uncertainty per line.

### 4 DISCUSSION

#### 4.1 Cluster membership of the planetary nebula

The *Spitzer* image of NGC 2438 extracted from the archive is very reminiscent of that of M57 with the multiple outer shells of molecular hydrogen seen to extend well outside the bounds of the well-known optical image. Interestingly here, a deep optical H\(\alpha\) image from the SuperCOSMOS H-alpha Survey (Parker et al. 2005), Fig. 2 clearly show faint optical emission too that matches the inner shell and part of the faint outer shell to the west seen in the mid-IR (see also fig. 7 in Corradi et al. 2003). The *Spitzer* data also reveal evidence of an interesting possible interaction of the molecular material with the interstellar medium at the south–eastern edge of the PN, pointing more or less away from the centre of the OC.

We present the measured PN emission line velocities in Table 2. The numbers show a very good agreement between the northern and southern edges, suggesting a mean velocity of 78 ± 2 km s\(^{-1}\). The only outlier is the P16 8502 line, however, that feature was significantly affected by the residual skylines at \(\lambda\lambda 8504.6–8505.1\) Å and their removal during the data reduction. The mean velocity value is also in perfect agreement with the average mid-point of the double-peaked [O III] lines in the centre (77.5 ± 1 km s\(^{-1}\)). We therefore adopt \(v_{PN} = 78 ± 2\) km s\(^{-1}\) as the radial velocity of NGC 2438, which is in excellent agreement with other published velocities in the literature (77 km s\(^{-1}\); Campbell & Moore 1918; 74 ± 4 km s\(^{-1}\); Meatheringham, Wood & Faulkner 1988; 74 ± 5 km s\(^{-1}\), Corradi et al. 2000), as well as an unpublished determination of 73 ± 6 km s\(^{-1}\) from a South African Astronomical Observatory (SAAO) 1.9-m long-slit spectrum (Frew 2008). On the other hand, from the relative velocity difference between the two peaks in the [O III] profiles, we measured an expansion velocity of 21.0 ± 0.2 km s\(^{-1}\), virtually identical, for instance, to what Corradi et al. (2000) reported from high-resolution H\(\alpha\) and [O III] spectra (21 km s\(^{-1}\)). In summary, our PN measurements draw a picture that agrees exceptionally well with other results in the literature, confirming the reliability of the determined velocities and quoted uncertainties.

Fig. 5 compares the mean PN velocity to the histogram of the newly derived cluster star velocities that represent the most extensive and accurate such data for M46 obtained to date. We confirm the early results that NGC 2438 has a relative velocity of about 30 km s\(^{-1}\) with respect to the cluster (O’Dell 1963), hence the nebula is not a bound member of the cluster despite being located approximately at the same ~1.5–1.7 kpc distance (MTL07, BBS08). In Fig. 5, we also put an arrow at the mean centre-of-mass velocity (48.5 km s\(^{-1}\)) of three red giant binaries measured by Mermilliod et al. (1989, 2007). The excellent agreement between the maximum of the histogram (49 km s\(^{-1}\) for the highest value, 48 km s\(^{-1}\) for the centroid of the fitted Gaussian) and the very accurate CORAVEL data confirms both the cluster membership of those systems and the quoted accuracy of our single-epoch velocity measurements.

#### Table 2. Measured PN velocities. See the text for a discussion of the uncertainties.

<table>
<thead>
<tr>
<th>Line</th>
<th>PN central (km s(^{-1}))</th>
<th>PN north (km s(^{-1}))</th>
<th>PN south (km s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>H(\beta) 4861</td>
<td>76.1</td>
<td>80.1</td>
<td></td>
</tr>
<tr>
<td>[O III] 4959</td>
<td>58.7, 100.2</td>
<td>78.6</td>
<td>79.8</td>
</tr>
<tr>
<td>[O III] 5007</td>
<td>55.6, 98.2</td>
<td>77.6</td>
<td>77.6</td>
</tr>
<tr>
<td>P16 8502</td>
<td>68.1</td>
<td>58</td>
<td></td>
</tr>
<tr>
<td>P15 8545</td>
<td>75.5</td>
<td>76.5</td>
<td></td>
</tr>
<tr>
<td>P14 8598</td>
<td>72.1</td>
<td>84.4</td>
<td></td>
</tr>
<tr>
<td>P13 8665</td>
<td>74.3</td>
<td>79.5</td>
<td></td>
</tr>
<tr>
<td>P12 8750</td>
<td>73.1</td>
<td>76.5</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4. Upper panel: the H\(\beta\) and [O III] doublet line profiles in the three observed positions. The centre ones are clearly double peaked. Lower panel: the near-IR spectra of the same three locations with line identifications. The dashed line shows the zero flux level for the central star, indicating the detection of a flat continuum. No continuum is seen in the nebular positions, whose spectra are dominated by the Paschen lines.

Figure 5. The histogram of stellar radial velocities for M46. The arrow shows the mean centre-of-mass velocity of three red giant binaries published by Mermilliod et al. (1989, 2007), while the smooth lines represent the Gaussian fits of the field and the cluster. About half of the observed stars belong to the cluster.
We also note that while this paper was under review, a new cluster radial velocity was published by Frinchaboy & Majewski (2008), who measured $+46.9 \pm 1.0 \text{ km s}^{-1}$ from 19 member stars. The nice agreement gives further support to our results.

We examined the possibility that the progenitor of NGC 2438 was a runaway star that has been ejected from M46, since it is the only option for maintaining possible physical association of the cluster and PN. Runaway stars escape from star clusters with velocities of typically $30 \text{ km s}^{-1}$ (Blaauw 1961; Hoogerwerf, de Bruijne & de Zeeuw 2001) and one cannot ad hoc exclude the possibility that something similar has happened in M46. However, we feel this to be quite unlikely. If we assume a binary-supernova scenario as a possible explanation, then the supernova (SN) must have happened $170–200 \text{ Myr ago}$ (i.e. the cluster age minus the evolutionary age of a progenitor star of $8 M_\odot$, the lower limit for a core-collapsing SN). A star travelling at $30 \text{ km s}^{-1}$ for this time traverses $5–6 \text{ kpc}$ in the absence of other forces, so that it should have left the apparent vicinity of the cluster a long time ago, unless its radial velocity is almost perfectly aligned along the line of sight. The other possibility could be a very recent ejection, most likely within the last couple of million years, as a part of a binary–binary dynamical ejection event. However, the dynamical ejection scenario (DES) requires a high-density environment in which close encounters of binaries can happen more frequently: young OCs or OB associations forming massive stars (Hoogerwerf et al. 2001). M46 is neither young nor has an exceptional high density compared to other intermediate-age OCs. Ultimately, future proper motion measurements could be used to distinguish between the option of chance projection and the option of runaway star.

In summary, while past membership of the progenitor cannot be completely ruled out, we can safely conclude against present membership of the PN in the cluster.

4.2 Evidence of a significant binary population of the cluster

We also noted the surprisingly large velocity dispersion of the cluster, indicated by the broad cluster peak of the histogram. While some of it might be explained by the degraded velocimetric accuracy for the hotter stars (cf. Section 3.1), the full range between 35 and $60 \text{ km s}^{-1}$ seems to be too large as purely due to measurement errors. We quantified the velocity dispersion by fitting two Gaussians to the histogram, one broad and one narrow to represent the Galactic background and the cluster members, respectively. The resulting line-of-sight velocity dispersion of the cluster is $\sigma_{\text{los}} = 3.9 \pm 0.3 \text{ km s}^{-1}$ (removing 78 stars with $T_{\text{eff}} > 10,000 \text{ K}$ changes the result to $\sigma_{\text{los}} = 3.8 \pm 0.2 \text{ km s}^{-1}$). This is a very high value for a relatively old OC and suggests the presence of many binaries. The velocity dispersion of the broad Gaussian is $18.4 \text{ km s}^{-1}$, which is consistent with field stars predominantly in the thin disk (Veltz et al. 2008).

As a simple exercise, we estimated the dynamical mass of the cluster using the equation $M_{\text{dyn}} = \eta R_\odot \sigma_{\text{los}}^2 / G$, where $R_\odot$ is the half-light radius, $G$ is the gravitational constant and $\eta$ is a dimensionless constant (Spitzer 1987). With this we also make the assumption that the cluster is in virial equilibrium, which is most likely the case, given that clusters older than $\sim 50 \text{ Myr}$ are expected to be in virial equilibrium (e.g. Goodwin & Bastian 2006). A rough estimate for the half-light radius of M46 can be taken as the core radius of 3.3 pc (Sharma et al. 2006). Similarly, about half of the likely members in our spectroscopic sample lie within 3.4 pc to the cluster centre. Assuming $R_\odot = 3.3 \text{ pc}$ and the canonical $\eta = 9.75$, the result is $M_{\text{dyn}} = 1.1 \times 10^7 M_\odot$.

On the other hand, adopting $V_{\text{rad}} = 6.1 \text{ mag}$ from SIMBAD and $V - M_V \approx 11.2 \text{ mag}$, the resulting absolute brightness $M_V = -5.1 \text{ mag}$ corresponds to $L_V/L_\odot \approx 8800$, leading to $L_V/M_{\odot} \lesssim 0.1$, which is way too low for any stellar cluster (see e.g. fig. 5 in Goodwin & Bastian 2006). Therefore, the dynamical mass must be grossly overestimated, which is a well-known effect when a significant binary population exists in a cluster (for a recent study see e.g. Kouwenhoven & de Grijs 2008). Other evidence that points in this direction was mentioned by Sharma et al. (2006), who noted that the broad main sequence in the colour–magnitude diagram could be due to the presence of binary stars. In that case, orbital motion can introduce extra velocity scatter, which can lead to significantly overestimated dynamical masses.

One caveat is the neglected effect of the radial velocity errors on the velocity dispersion. If the real errors are much larger than the quoted formal errors from the cross-correlation (cf. Section 3.1), then the velocity dispersion could be dominated by measurement errors, hence getting only an upper limit to $\sigma_{\text{los}}$ and $M_{\text{dyn}}$ and a lower limit on $L_V/M_{\odot}$. Our experiences with the same instrument and data on other, mostly globular, star clusters (Kiss et al. 2007; Szelély et al. 2007) showed that high-S/N AAOmega spectra can reproduce published radial velocities with the quoted $\pm 1–2 \text{ km s}^{-1}$ accuracy for stars cooler than $\sim 6000 \text{ K}$. For M46, we have neither repeated observations nor independent measurements with other instruments to check the precision and the accuracy of the velocities, but with the good S/N for most of the data, we are confident that the dispersion is not dominated by the measurement errors.

5 SUMMARY AND FUTURE WORK

The results of this paper can be summarized as follows.

(i) We have obtained medium-resolution optical and near-IR spectroscopy for the OC M46 and the putative associated PN NGC 2438. A careful analysis of the data firmly established a mean radial velocity difference of about $30 \text{ km s}^{-1}$ between the two objects. While the available data do not rule out past physical association if the star has been ejected, their mutual distance is currently increasing at least by $30 \text{ pc Myr}^{-1}$, hence rejecting present membership of the nebula.

(ii) The histogram of the radial velocities has been fitted with a sum of two Gaussians, representing the smooth galactic field and the cluster. Roughly half of the 586 stars belong to the cluster, while the rest have a velocity dispersion of about $18.4 \text{ km s}^{-1}$, that is characteristic for the thin disk. The line-of-sight dispersion of the cluster is $3.9 \text{ km s}^{-1}$, which implies an unrealistically large dynamical mass. This could be due to the presence of a significant population of binary stars or larger than assumed velocity errors or the combination of both. The large intrinsic width of the main sequence in the colour–magnitude diagram supports the binary explanation.

Future work should address proper motions of individual stars to investigate if the PN progenitor was a runaway star ejected from the cluster. While GAIAD will measure very accurate proper motions from space, there might also be historical photographic plates that are suitable for determining proper motions. We make all the radial velocity data available through an electronic appendix to this paper. Combined with multicolour photometric data from the literature (e.g. through the WEBDA data base), these will be used to create an

http://www.univie.ac.at/webda/
accurate colour–magnitude diagram of the cluster largely cleaned of the Galactic background and foreground.

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APPENDIX A: THE DATA

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article.

Table A1. Radial velocities of the observed stars. The full data set is available in the online version of this paper.

<table>
<thead>
<tr>
<th>RA (J2000)</th>
<th>Dec. (J2000)</th>
<th>$v_r$ (km s$^{-1}$)</th>
</tr>
</thead>
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<tr>
<td>115.634 333 32</td>
<td>−14.836 119 44</td>
<td>58.4</td>
</tr>
<tr>
<td>115.575 458 32</td>
<td>−14.924 483 33</td>
<td>50.1</td>
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<tr>
<td>115.673 749 98</td>
<td>−14.908 316 66</td>
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<td>115.747 333 32</td>
<td>−14.843 680 55</td>
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<td>115.885 041 65</td>
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<td>−14.864 088 89</td>
<td>54.4</td>
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