Abundance analysis of the J4 equatorial knot of the born-again planetary nebula Abell 30

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ABSTRACT

Abell 30 belongs to a class of planetary nebulae identified as ‘born-again’, containing dense, hydrogen-poor ejecta with extreme abundance discrepancy factors, likely associated with a central binary system. We present intermediate-dispersion spectroscopy of one such feature – the J4 equatorial knot. We confirm the apparent physical and chemical segregation of the polar and equatorial knots observed in previous studies, and place an upper limit on the abundance discrepancy factor for O$^{2+}$ of 35, significantly lower than that of the polar knots. These findings further reinforce the theory that the equatorial and polar knots originate from different events.

Keywords: Circumstellar matter(241) – Interstellar abundances(832) – Common envelope binary stars(2156) – Planetary nebulae(1249)

1. INTRODUCTION

The disparity between abundances derived from recombination lines (RLs) and collisionally excited lines (CELs), the ratio of which is known as the abundance discrepancy factor (ADF), was first observed almost 80 years ago (Wyse 1942), but its origin is still unclear. ADFs are typically 2-3 in planetary nebulae (PNe; García-Rojas et al. 2013), although in some cases the ADF can reach 2-3 orders of magnitude (Wesson et al. 2003). Many explanations for these discrepancies have been proposed, including chemical (Torres-Peimbert et al. 1990), density (Gruenwald & Viegas 1995), and temperature inhomogeneities (Torres-Peimbert et al. 1980), hydrogen-deficient knots (Liu et al. 2000), and orbitally-induced temperature resonances (Bautista & Ahmed 2017). Recently, a link between these high abundance discrepancy PNe and the binarity of their central stars has become evident (Wesson et al. 2018).

Abell 30 (A 30) presents the highest measured ADF (∼700) in one of its knot complexes (Wesson et al. 2003) and is suspected to host a close binary central star (Jacoby et al. 2020). A 30 also belongs to a small subset of PNe identified as ‘born-again’, characterised by the presence of low mass, hydrogen-deficient knots. The low C/O ratio measured in the ionised component of the knots led Wesson et al. (2003) to to argue that they could not have originated in a born-again event, and to suggest a relation to classical novae instead; Lau et al. (2011) identified scenarios in which the knots could be formed by an eruptive event on a ONeMg white dwarf. However, Toalá et al. (2021) have recently shown that most of the nebular carbon is in the form of dust and that the total C/O ratio is >1 – more consistent with a
very-late thermal pulse scenario. The knots themselves comprise two components – a polar jet (J1 and J3), and an equatorial disk (J2 and J4).

Here, we build upon the study of the polar knots by Wesson et al. (2003) through the analysis of spectra obtained of the equatorial J4 knot of A 30.

2. OBSERVATIONS AND DATA REDUCTION

A 30 was observed with the Intermediate-dispersion Spectrograph and Imaging System (ISIS) on the 4.2-m William Herschel Telescope (WHT) on February 16 2017. The setup was replicated from the study of Wesson et al. (2003), as were the individual exposure times of 1800s. Six exposures were taken in each arm for a total time on target of 3 hours. The slit was centred on the central star at a position angle of 12°, in order to obtain a spectrum of the J4 knot (see Figure 1).

3. CHEMICAL AND PHYSICAL PROPERTIES

The extinction, $c(H\beta) = 1.26$, was obtained from the Balmer decrement. This is significantly higher than the value for J1 and J3 (Wesson et al. 2003), and also differs from the analysis of Guerrero & Manchado (1996), who do not correct for extinction. Ultimately, the extinction depends on the adopted electron temperature ($10^4$ K), and is uncertain in the knots due to their low hydrogen abundances.

The electron density was measured from a weighted mean of the [O II] $\lambda3726/\lambda3729$ and [S II] $\lambda6716/\lambda6732$ line ratios, giving $n_e = 650 \pm 130 \text{ cm}^{-3}$. Adopting this value, the temperature of the knot is then calculated using the [O III] ($\lambda4959 + \lambda5007/\lambda4363$) ratio to be $T_e = 14675 \pm 730$ K. This is in agreement with the value obtained by Guerrero & Manchado (1996) of $T_e = 14000 \pm 1000$ K, however the density value obtained is much higher than their value of $n_e = 250 \text{ cm}^{-3}$.

The relative oxygen abundance was calculated as $12 + \log O/H = 9.72^{+0.27}_{-0.10}$, which is just about within the bounds of the value from Guerrero & Manchado (1996) of $9.51^{+0.11}_{-0.14}$. The relative abundances of nitrogen and helium are in agreement with those of Guerrero & Manchado (1996), with obtained values of $12 + \log N/H = 9.18^{+0.18}_{-0.21}$ and $12 + \log He/H = 12.62^{+0.18}_{-0.17}$. Additionally, relative abundances of Ne, S, Ar$^{2+}$, and Ar$^{3+}$ were measured as $12 + \log Ne/H = 9.25^{+0.18}_{-0.17}$, $12 + \log S/H = 6.96^{+0.27}_{-0.18}$, $12 + \log Ar^{2+}/H = 6.82^{+0.21}_{-0.17}$, $12 + \log Ar^{3+}/H = 7.18^{+0.22}_{-0.17}$. The abundance of C$^{2+}$ was measured as $12 + \log C^{2+}/H = 10.70$ which, assuming C/O$\sim$C$^{2+}$/O$^{2+}$, implies a C/O ratio of 0.5–0.9 consistent with the value found for the J1 and J3 knots (Wesson et al. 2003).

In spite of the high ADF observed for the polar knots, the recombination lines of J4 are very faint (see Fig. 1). The only species we detect both in recombination lines and collisionally excited lines is doubly-ionised oxygen, where there is a low signal-to-noise detection of the O II lines at $\lambda4641$ and $\lambda4649 + 50$ Å. This detection leads to an approximate ADF(O$^{2+}$) $\sim$ 22. However, the $\lambda4641$ line is likely contaminated by N III due to the high excitation of the nebula, and the $\lambda4649 + 50$ line appears to be blended with a C III line. Ultimately, the ADF of J4 is highly uncertain, however assuming no N III contamination, we derive an upper limit of ADF(O$^{2+}$) $= 35$.

4. CONCLUSIONS

New spectroscopic observations of the equatorial J4 knot reaffirm the apparent chemical and physical segregation of the polar and equatorial knots of A 30 (Guerrero & Manchado 1996). A low signal-to-noise detection of O II ORLs places an upper limit on the ADF(O$^{2+}$) $= 35$, at least one order of magnitude lower than that observed in the polar knots. However, without knowing the mass fraction between the H-poor and H-rich gas phases, the ADF cannot be used as a probe of their relative abundances (Gómez-Llanos & Morisset et al. 2003).
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2020). As such, the J4 knot may have similar total abundances to those of the polar knots, but simply present with a different (lower) ratio of H-poor to H-rich material. Ultimately, detailed three-dimensional, bi-phase photo-ionisation modelling will be required in order to further constrain the properties and origins of the H-deficient knots.

Facilities: WHT(ISIS), HST
Software: PyNeb (Luridiana et al. 2015) ALFA (Wesson 2016) NEAT (Wesson et al. 2012)

REFERENCES

Bautista, M. A., & Ahmed, E. E. 2017, arXiv e-prints, arXiv:1709.07945. https://arxiv.org/abs/1709.07945
Fang, X., Guerrero, M. A., Marquez-Lugo, R. A., et al. 2014, ApJ, 797, 100, doi: 10.1088/0004-637X/797/2/100
García-Rojas, J., Peña, M., Morisset, C., et al. 2013, A&A, 558, A122, doi: 10.1051/0004-6361/201322354
Gómez-Llanos, V., & Morisset, C. 2020, MNRAS, 497, 3363, doi: 10.1093/mnras/staa2157
Gruenwald, R., & Viegas, S. M. 1995, A&A, 303, 535
Guerrero, M. A., & Manchado, A. 1996, ApJ, 472, 711, doi: 10.1086/178101
Jacoby, G. H., Hillwig, T. C., & Jones, D. 2020, MNRAS, 498, L114, doi: 10.1093/mnrasl/slaa138
Lau, H. H. B., De Marco, O., & Liu, X. W. 2011, MNRAS, 410, 1870, doi: 10.1111/j.1365-2966.2010.17568.x
Liu, X.-W., Storey, P. J., Barlow, M. J., et al. 2000, Monthly Notices of the Royal Astronomical Society, 312, 585, doi: 10.1046/j.1365-8711.2000.03167.x
Luridiana, V., Morisset, C., & Shaw, R. A. 2015, A&A, 573, A42, doi: 10.1051/0004-6361/201323152
Toalá, J. A., Jiménez-Hernández, P., Rodríguez-González, J. B., et al. 2021, MNRAS, 503, 1543, doi: 10.1093/mnras/stab593
Torres-Peimbert, S., Peimbert, M., & Dalaltubit, E. 1980, ApJ, 238, 133, doi: 10.1086/157966
Torres-Peimbert, S., Peimbert, M., & Pena, M. 1990, A&A, 233, 540
Wesson, R. 2016, MNRAS, 456, 3774, doi: 10.1093/mnras/stv2946
Wesson, R., Jones, D., García-Rojas, J., Boffin, H. M. J., & Corradi, R. L. M. 2018, MNRAS, 480, 4589, doi: 10.1093/mnras/sty1871
Wesson, R., Liu, X. W., & Barlow, M. J. 2003, MNRAS, 340, 253, doi: 10.1046/j.1365-8711.2003.06289.x
Wesson, R., Stock, D. J., & Scicluna, P. 2012, MNRAS, 422, 3516, doi: 10.1111/j.1365-2966.2012.20863.x
Wyse, A. B. 1942, ApJ, 95, 356, doi: 10.1086/144409