The conjectured S-type retrograde planet in $\nu$ Octantidis: more evidence including four years of iodine-cell radial velocities

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ABSTRACT

We report 1212 radial-velocity (RV) measurements obtained in the years 2009-2013 using an iodine cell for the spectroscopic binary $\nu$ Octantidis (K1III/IV). This system ($a_{\text{bin}} \sim 2.6$ au, $P \sim 1050$ days) is conjectured to have a Jovian planet with a semi-major axis half that of the binary host. The extreme geometry only permits long-term stability if the planet is in a retrograde orbit. Whilst the reality of the planet ($P \sim 415$ days) remains uncertain, other scenarios (stellar variability or apsidal motion caused by a yet unobserved third star) continue to appear substantially less credible based on CCF bisectors, line-depth ratios and many other independent details. If this evidence is validated but the planet is disproved, the claims of other planets using RVs will be seriously challenged.

We also describe a significant revision to the previously published RVs and the full set of 1437 RVs now encompasses nearly 13 years. The sensitive orbital dynamics allow us to constrain the 3D architecture with a broad prior probability distribution on the mutual inclination, which with posterior samples obtained from an $N$-body Markov chain Monte Carlo is found to be $152.5^\circ \pm 0.7^\circ$. None of these samples are dynamically stable beyond $10^8$ years. However, a grid search around the best-fitting solution finds a region that has many models stable for $10^7$ years, and includes one model within 1-sigma that is stable for at least $10^8$ years. The planet’s exceptional nature demands robust independent verification and makes the theoretical understanding of its formation a worthy challenge.

Key words: techniques: radial velocities – planets and satellites: dynamical evolution and stability, – binaries: spectroscopic – stars: individual: $\nu$ Octantidis –

1 INTRODUCTION

It has been speculated from several years of radial velocity (RV) observations that the single-lined spectroscopic binary (SB1) $\nu$ Octantis hosts a Jovian planet (Ramm 2004; Ramm et al. 2009). Given the present scale of exoplanet discoveries, this may not seem too unusual. However, the binary has by far the tightest geometry of any proposed to harbour a circumstellar (i.e. S-type) planet, having a mean separation of only $a_{\text{bin}} \sim 2.6$ au. The minimum-separation barrier is presently tentatively at about 20 au, as will be described in more detail shortly. Furthermore, the RV signal, if it is caused by a planet, places its circumprimary orbit about midway between the stars i.e. $a_{pl} \sim 0.5a_{\text{bin}}$. For a prograde orbit, models predict long-term stability should be limited to about half this distance i.e. $a_{pl} \lesssim 0.25a_{\text{bin}}$ (Holman & Wiegert 1999; Ramm et al. 2009; Eberle & Cuntz 2010; Andrade-Ines et al. 2016). However if the planet is in a retrograde orbit, as first suggested by Eberle & Cuntz (2010), the stability zone is wider (Jefferys 1974; Morais & Giuppone 2012), and places the conjectured orbit very near and perhaps within the boundary of stability. As extraordinary as the retrograde scenario may appear, since its very formation would also be challenged by strong dynamical interactions, the alternative standard explanations of instrumental or data reduction anomalies, starspots, pulsations or apsidal motion of the binary orbit are less supported by the observational evidence (Ramm et al. 2009; Ramm 2015). Other retrograde planets have been postulated but in each of them a choice exists between viable prograde and retrograde options (see

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### Table 1. Stellar parameters for \( \nu \) Oct. 1: Mermilliod (1991), 2: present work, 3: ESA (1997), 4: Costa et al. (2002); 5: Ramm et al. (2009), 6: Fuhrmann & Chini (2012). Fuhrmann & Chini revised the primary mass and radius estimates given in Ramm et al. (2009), based in particular on their metallicity. Their \( \sigma \) errors are halved here to be consistent with the \( L \) errors used elsewhere here. \( \dagger \) We suspect the luminosity class may be evolved at most IIIb - IV (see the Discussion).

| Parameter | \( \nu \) Octantis A | Reference |
|-----------|----------------------|-----------|
| Spectral type | K0III \( \dagger \) | (3) |
| \( V \) (mag) | \( 3.743 \pm 0.015 \) | (1) |
| \( M_V \) (mag) | \( +2.02 \pm 0.02 \) | (2) |
| \( B - V \) | \( 0.992 \pm 0.004 \) | (1) |
| \( H_p \) (Hipparcos mag) | \( 3.898 \pm 0.0004 \) | (3) |
| Mass (\( M_{\odot} \)) | 1.61 | (6) |
| Radius (\( R_{\odot} \)) | \( 5.81 \pm 0.12 \) | (6) |
| \( T_{\text{eff}} \) (K) | \( 4.860 \pm 40 \) | (6) |
| \( \log g \) (cgs) | \( 3.12 \pm 0.10 \) | (6) |
| \( [Fe/H] \) (dex) | \( +0.12 \pm 0.04 \) | (6) |
| \( v \sin i \) (km s\(^{-1}\)) | 2.0 | (4), (6) |
| Age (Gyr) | \( \sim 2.5 - 3 \) | (5) |

### Table 2. Orbital parameters for \( \nu \) Oct A and the conjectured planet from 222 RVs (Ramm et al. 2009) and Hipparcos astrometry. The Keplerian elements are the RV semi-amplitude \( K \), period \( P \), eccentricity \( e \), the argument of periastron \( \omega \). The scaled masses are based on the revised primary mass. Each relative orbit’s semimajor axis \( a \) is derived from Kepler’s Third Law, and assumes coplanar orbits.

| Parameter | \( \nu \) Oct A’s absolute orbits | \( \nu \) Oct B | conjectured planet |
|-----------|----------------------------------|----------------|---------------------|
| companion | \( K_1 \) (km s\(^{-1}\)) | \( 7.032 \pm 0.003 \) | \( 0.052 \pm 0.002 \) |
| \( P \) (days) | \( 1050.1 \pm 0.1 \) | \( 417.4 \pm 3.8 \) |
| \( e \) | \( 0.2359 \pm 0.0003 \) | \( 0.12 \pm 0.04 \) |
| \( \omega \) (°) | \( 75.05 \pm 0.05 \) | \( 260 \pm 21 \) |
| \( i \) (°) | \( 70.8 \pm 0.9 \) | \( - \) |
| \( \Omega \) (°) | \( 87 \pm 1.2 \) | \( - \) |
| \( M \sin i \) (\( M_{\odot} \)) | \( 0.55 \) | \( 2.4 - (M_{\text{Jup}}) \) |
| \( a \) (au) | \( 2.6 \pm 0.1 \) | \( 1.3 \pm 0.1 \) |
| RMS (m s\(^{-1}\)) | \( 19 \) | \( (\chi^2)^{1/2} \) | 4.2 |

Platoan systems may exist in binary systems in either P-type (in the present context, circumbinary) or S-type (circumstellar) configurations. Of the confirmed binaries harbouring S-type planets, all have stellar separations exceeding that of \( \nu \) Oct by an order of magnitude or so. Zhou et al. (2012) and Wang et al. (2014) identify the apparent barrier of about 20 au to such orbits based on the accepted planet-hosting binaries. These include GJ 86 A (Queloz et al. 2000), HD 41004 A (Zucker et al. 2004), and HD 196885 A (Correia et al. 2008; Thébault 2011). One of the first exoplanet claims was for \( \gamma \) Cephei A (Campbell, Walker & Yang 1988) which was then understandingly challenged (Walker et al. 1992). Eleven years elapsed before Hatzes et al. (2003) provided evidence that vindicated that planet’s reality. An S-type planet was claimed for \( \alpha \) Cent B (Dumusque et al. 2012; \( a_{\text{bin}} \sim 17.5 \) au) though the planet orbit is tiny (\( a_{\text{pl}} = 0.04 \) au). Its existence has been challenged (Hatzes 2013) and more recently by Rajpaul, Aigrain & Roberts (2016). The planet claimed for the hierarchical triple HD 188753 (Konacki 2005; \( a_{\text{bin}} \sim 13 \) au) also appears to be non-existent (Eggenberger et al. 2007). All accepted S-type systems have separation ratios much smaller than that implied for \( \nu \) Oct, with \( \gamma \) Cep, HD 196885 and HD 41004 all having \( a_{\text{pl}}/a_{\text{bin}} \sim 0.1 \). It is thus hardly surprising that the \( \nu \) Oct planet remains unconfirmed and controversial, even though it may so far ‘pass’ many standard tests for such a claim, as the above-mentioned discredited planets also originally did.

Thus there is no direct observational precedent for a planet to exist in such circumstances though, for instance Trilling et al. (2007) gives some indirect evidence based on infra-red excesses of main-sequence binaries. The \( \nu \) Oct system also presents
formidable theoretical challenges and many papers explore the formation and stability of S-type systems, such as Chauvin et al. (2011), Thébault (2011), Müller & Kley (2012), Jang-Condell (2015), and Rafikov & Silsbee (2015). The planet forming coevally with the present binary orbit is inconsistent with our present understanding of such processes, even if the original orbit was prograde. Rafikov (2013) studied planetesimal formation in small-separation binaries (again at the ‘barrier’ $a_{\text{bin}} \sim 20$ au) and found that sufficiently massive axisymmetric disks may eliminate the fragmentation barrier for the formation of giant planets in these ‘tight’ systems. Whether or not these findings or related ones can ultimately extend to the extreme demands of $\nu$ Oct remains to be determined. Hence, it is not surprising that such tight binaries are rarely included in S-type planet search programmes, and this bias may underlie (though surely unexpectedly) their lack of discovery.

Since coeval formation is presently so unbelievable, more credible alternatives must be considered, no matter how exotic they may presently seem. A strong gravitational event (e.g. a passing star) is not so extreme. This multi-faceted possibility includes variations such as capture of one other star or a planet-hosting star. Furthermore, the planet was originally hosted by the secondary and somehow exchanged (see e.g. Kratter & Perets 2012; not surprisingly, their work focussed on more manageable binary models having e.g. separations of 75–105 au). Tutukov & Fedorova (2012) describe other atypical planet formation scenarios, including one conjectured to yield retrograde orbits by passage of the host through a dense rotating molecular cloud.

This paper continues the search for the cause of the RV behaviour of $\nu$ Oct. In Section 2 we describe the nearly 13 years of data and the two instrument setups, the second including a larger detector and iodine cell. Section 3 presents our RV datasets, including the new iodine-cell velocities acquired between 2009 and 2013, and a critical revision of the older CCF RVs (2001–2007) reported in Ramm et al. (2009). We also provide preliminary orbital solutions, at this point abbreviations of our simple double-Keplerian model. In Section 4 we assess Ca II H line, cross-correlation function (CCF) bisectors, and line-depth ratios. Section 5 provides our 3-D dynamical orbital solutions, and our stability modelling results are given in Section 6. Section 7 discusses three additional system details: our derived space velocities, the benefits of future astrometry and imaging opportunities, and the nature of the system’s initial discovery. The Discussion evaluates the various possible causes of the mysterious RV signal. The paper concludes that the hypothesis, that the RV signal is caused by a retrograde planet, still has the most support from the observations.

2 OBSERVATIONS AND REDUCTIONS

2.1 Spectrograph and CCD detectors

All spectroscopic observations were obtained at University of Canterbury Mt. John Observatory, Lake Tekapo, New Zealand using the 1-m McLellan telescope and the échelle spectrograph HERCULES (Hearnshaw et al. 2002; Ramm 2004). From the start of operations in 2001 until 2006/7 the detector was a 1k × 1k detector. Initial testing of a complete-wavelength-coverage 4k × 4k detector began in October 2006. This detector was then removed briefly and the original detector used until the 4k × 4k CCD was installed permanently in early 2007.

2.2 Observations

As well as $\nu$ Oct’s many favourable spectral and photometric characteristics for precise RVs, its airmass at Mt. John (latitude 43° S) never exceeds 1.9 due to its far southern declination ($\sim$ −77°).

2.2.1 1k × 1k CCD (2001–2007)

In addition to the 222 observations (2001–2006) reported in Ramm et al. (2009), a further 21 spectra were obtained over four consecutive nights February–March 2007 between the detector changes described above and extend the time-span of observations with this detector to nearly 2100 days. It has also been decided to reject eighteen of the Ramm et al. paper’s spectra from our final analyses as it has been recognised they were probably acquired in circumstances making their reliability and quality questionable. Thus 225 RV spectra were included from this detector, 215 with a resolving power $R \sim 70\,000$ and ten with $R \sim 41\,000$. The typical exposure time for stellar spectra was 3–5 minutes which provided an average signal-to-noise ratio $S/N = 122 \pm 16$ in the middle of order $n = 110$ ($\lambda \sim 5170$ Å).

2.2.2 4k × 4k CCD (2006–2013)

During the brief initial commissioning of this detector in late 2006 (but without the I$_2$ cell), two $\nu$ Oct spectra were taken on the night of October 15 (JD 245 4024). When this larger CCD was installed permanently in early 2007, the I$_2$ cell was included, positioned just before the Cassegrain focus. The cell was maintained at 50° C and provided a dense imprint of molecular absorption lines from 5000 to 6200 Å. This cell was replaced in March 2011 by one promising to provide somewhat stronger spectral lines. A pinhole relay system was installed in March 2011 in front of the fibre entrance. The pinhole was included for the benefit of a parallel programme observing $\alpha$ Cen (Endl et al. 2015), whose increasingly narrow angular separation contributed significant cross-contamination. The pinhole reduced the light throughput by about half and eventually (April 2013) it could be removed when required.

All spectra obtained with this detector used $R \sim 70\,000$. Stellar exposure times were generally 12–20 minutes with the pinhole, and 7–15 minutes without it. A total of 1180 spectra had iodine-cell RVs derived from them, having an average $S/N = 113 \pm 26$. A further 32 spectra could only have a CCF RV derived, and fell into two groups: 22 RV exposures with $S/N = 157 \pm 44$ and ten Ca II-related exposures averaged 349 ± 40. Thus there are 1233 new RV spectra reported from both detectors.

Initially only spectral orders $n = 86–116$ were recorded. From December 2010, the readout was extended to $n = 129$, beyond which inadequate $S/N$ was found for our standard RV exposures. These blue orders promise more precise CCF RVs, and critically, would be needed for our CCF bisector measurements. These orders would also allow us to recover RVs for 4k × 4k spectra for which I$_2$-cell processing proved unachievable, and allow us to significantly improve the precision of the 1k × 1k RVs presented in Ramm et al. (2009) ($\S$ 3.1.1 and $\S$ 3.2).

$^2$ See Ramm (2015; $\S$ 2.1.1) for an explanation of these additions and rejections.

$^3$ However, as Table 2 will reveal, the mean internal RV error for our $\nu$ Oct spectra actually increased by 0.7 m s$^{-1}$ with this change.
Table 3. An abbreviated list of the 1180 AUSTRAL-processed I2 spectra acquired during 2009-2013 using the 4k × 4k CCD including barycentric-corrected Julian date, corrected relative velocity $V_{i2}$, internal error $\sigma_i$, and barycentric correction, and the $S/N$ in order $n = 110$. The entire table is provided online.

| JD        | $V_{i2}$ (km s$^{-1}$) | $\sigma_i$ (km s$^{-1}$) | bary.corr. (km s$^{-1}$) | $S/N$ |
|-----------|------------------------|---------------------------|--------------------------|-------|
| 4854.1147 | 3.925                  | 3.6                       | 3.5271                   | 84    |
| 4854.1190 | 3.926                  | 3.6                       | 3.5302                   | 88    |
| 4854.1226 | 3.923                  | 3.5                       | 3.5329                   | 89    |
| 4854.1270 | 3.931                  | 3.7                       | 3.5360                   | 85    |
| 4855.1861 | 3.958                  | 4.3                       | 3.8538                   | 72    |

2.3 Preliminary spectral reductions

The non-iodine part of each reduction was carried out using the Hercules Reduction Software Package HRSP v.3 for the 4k × 1k spectra (Skuljan 2004; also see Ramm 2004 for improvements to CCF RVs) and HRSP v.5 for the 4k × 4k spectra. Standard methods of échelle spectral reduction were utilised that included background subtraction and cosmic ray filtering. A quartz white lamp was used for flat fielding and normalization. Th-Ar spectra were obtained immediately before and after the stellar exposures for wavelength calibration. This latter requirement was critical for the CCF-derived RVs. The 257 CCF and 1180 I2 RVs were derived using CCFs. Here we describe the unconventional strategy used to derive the CCF-order weights to yield RVs with accuracies comparable to the I2 RVs.

Our only assumption was that the I2 RVs are a far more accurate gauge than typical HERCULES CCF RVs, easily justified by the vast literature supporting this detail, and avoids the assumption of a specific model as Ramm et al. (2009) did. A continuous series of 561 4k × 4k stellar spectra was selected that provided I2 RVs and the 16 non-I2 orders $n = 114 – 129$. These covered a time-span approximating one binary period of ~ 1050 days and thus the full range of $\nu$ Oct RVs. This series began on the first night the required blue orders were recorded (JD 245 5534) and ended on JD 245 6566. They are identified in Fig. 3. A high S/N spectrum was used as the reference to create the CCFs for these 16 orders $n$. We used the wider $n\lambda$ limits available with this larger detector ($\sim 50$ Å) and a Gaussian for fitting. The difference between the I2 RV and the CCF RV for each order was calculated for the 561 spectra $i$:

$$\Delta V_{i,n} = V_{i2,i} - V_{CCF,i,n},$$

and the corresponding standard deviation of these differences ($\sigma_{\Delta V}$) calculated, each difference weighted by the error on $V_{i2}$.

Our goal was to find the Gaussian that provided the smallest average of the sixteen $\sigma_{\Delta V}$ values. This set of Gaussians increased in radius from the CCF core in steps of ±1 bin from a minimum $r_{\text{ga}} = \pm 4$ bins, to one that assured us the optimum radius had been identified. The standard deviations for each order for the optimum radius determined its relative weight: $w_i = 1/\sigma_{\Delta V}^2$. Finally, due to their differing reference spectra, the I2 and CCF RVs have different velocity zero-points. Their offset, incorporated into the final published velocities, $V_i$, was $V_{\text{off}} = -3.987 \pm 0.010$ km s$^{-1}$. The total error assigned to each CCF $V_i$ was this offset error ($\pm 10$ m s$^{-1}$) added in quadrature to the spectrum’s internal error. The 32 4k × 4k CCF RVs are presented in Table 4. The mean error, not including the rather isolated first pair in October 2006 (JD 245 4024), is $16 \pm 3$ m s$^{-1}$. The substantially larger errors on the two RVs from 2006 are presumably related to their more distant acquisition time and the changing of the CCDs during 2006/7.

It is relatively simple to check if these CCF RVs are likely to be reliable, since we can assess their accuracy relative to I2 RVs.

Table 4. An abbreviated list of the relative velocity data of 32 4k × 4k detector observations acquired 2006-2013 using CCF fitting. Columns as for Table 3. The table is reproduced in full online.

| JD          | $V_{CCF}$ (km s$^{-1}$) | $\sigma_i$ (m s$^{-1}$) | bary.corr. (km s$^{-1}$) | $S/N$ (n = 110) |
|-------------|-------------------------|-------------------------|--------------------------|-----------------|
| 4024.1070   | 9.562                   | 52                      | -15.9816                 | 123             |
| 4024.1202   | 9.557                   | 52                      | -15.9813                 | 127             |
| 5728.2797   | -0.638                  | 15                      | 6.7807                   | 186             |
| 5816.9981   | 1.626                   | 12                      | -13.7272                 | 224             |
| 5819.9725   | 1.704                   | 16                      | -14.1085                 | 117             |

RVs were derived using CCFs. Here we describe the unconventional strategy used to derive the CCF-order weights to yield RVs with accuracies comparable to the I2 RVs.

3 RADIAl VELOCITIES

The 257 CCF and 1180 I2 radial velocities give a total of 1437 RVs sampling a time-span of nearly 4600 days or about 12.5 years. The method for deriving the 4k × 4k RVs is given first as it is conventional and straightforward. These I2 RVs were also required for determining, by a novel strategy, the 257 CCF RVs with higher precision than had been previously achievable with HERCULES.

3.1 4k × 4k detector RVs

Three high S/N iodine-free template spectra of $\nu$ Oct were co-added to form a single reference spectrum. Analysed in conjunction with high S/N spectra of the relatively line-free B-stars $\beta$ Centauri and $\alpha$ Eridani, all obtained close in time, this reference was deconvolved from the instrument profile using the Maximum Entropy Method. The RVs were derived with the pipeline AUSTRAL (Endl, Kürster & Els 2000) using fourteen orders. An abbreviated list of the final velocities, $V_{i2}$, is given in Table 3. The mean error is 3.6 ± 0.5 m s$^{-1}$. We also include our barycentric corrections and $S/N$ estimates for order $n = 110$.

3.1.1 Using I2 RVs as a gauge to derive CCF RVs

Thirty-two 4k × 4k spectra could not be fully processed by AUSTRAL. Instead, using the orders blueward of the I2 forest, their

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controversial weighting strategy to the older accuracy to ones derived with a sample, they suggest that if the weighting of the CCF orders is determined accurately, the resulting RVs can be of comparable accuracy to ones derived with an I2 cell. Assessing the credibility of the controversial ν Oct planet and any competing scenarios depends on RVs of the highest quality. Hence we will now apply this order-weighting strategy to the older 1k×1k spectra reported in Ramm et al. (2009).

3.2 Revision of 1k×1k CCF RVs

Unfortunately, the CCF RVs reported in Ramm et al. (2009) have several suspicious features that suggest a revision of them is prudent. For instance, the old internal errors (typically 4–6 m s\(^{-1}\)) are similar to our I2-RV errors, a Keplerian model was used to derive the spectral order weights, and perhaps most suspicious of all, \((\chi^2)^{1/2} = 4.2\) (Table 2), easily accounted for by the likelihood the errors are under-estimated.

To derive the CCF RVs from the 561 4k×4k spectra, we now have to restrict the number of examined orders \((n = 114–124)\) and the width of each order (\(\sim 20\) Å) to match the older 1k×1k spectra. Since the gauge and star are the same, and the only instrumental difference is the pixel size, which is identical across all orders for each detector, we claim the weighting strategy remains valid. The simple Keplerian solutions that duplicate the orbital fitting used in Ramm et al. will support this claim by nearly halving the solution RMS.

A different reference spectrum to that used in Ramm et al. was used here, having a higher \(S/N\sim 260\), which promised somewhat better RV precision. To avoid the reference spectrum’s internal error being zero (a consequence of the auto-correlation CCF process), all 1k×1k spectra had a minimal jitter term of 3 m s\(^{-1}\) added in quadrature to their errors, this being approximately the average error for the I2 RVs. This adjustment will be given careful reappraisal during the MCMC dynamical orbit-fitting analysis to give a properly refined estimate of any jitter terms.

The internal errors have a number of characteristics that suggest significant improvements to the original ones (Fig. 1): 1. almost all are significantly greater than our I2-RV errors (by a mean factor of about 3×, similar to the 2009 paper’s suspicious \((\chi^2)^{1/2}\), 2. their mean magnitude (15 ± 4 m s\(^{-1}\)) is more consistent with the anticipated possible precision of a HERCULES-CCF orbital solution, and 3. their values cover a much wider range, a sensible reflection of the varied observatory conditions experienced by DJR during 2001-2006. A plot of all our 1437 velocities is given in Fig. 3.

| JD    | \(V_{CCF}\) | \(\sigma_i\) | bary.corr. | \(S/N\) |
|-------|-------------|-------------|------------|--------|
| 245... | (km s\(^{-1}\)) | (m s\(^{-1}\)) | (km s\(^{-1}\)) | (n = 110) |
| 2068.0607 | 34 | 8.6469 | 128 |
| 2102.1137 | 19 | 0.0825 | 129 |
| 2121.0920 | 13 | 4.8861 | 137 |
| 2180.8839 | 27 | 15.3966 | 134 |
| 2219.8985 | 18 | 14.5397 | 96 |

Table 5. An abbreviated list of the 225 spectra acquired during 2001-2007 using the 1k×1k CCD. Columns as for Table 3. The entire table is provided online.
3.3 Preliminary orbital solutions – Keplerian

Keplerian orbital solutions are not adequate to model the conjectured \nu Oct system. However they serve a useful purpose if some of their details are given immediately, for instance, to demonstrate the improved precision of the older CCF RVs (the goal of §3.2), and to illustrate the strong persistent RV signal that all competing scenarios must explain. The actual elements are not critical for the paper’s progress except to point out they are in close agreement with the values reported by Ramm et al. (2009), in particular the elements of the conjectured planet include $P_{pl} \sim 415$ days, $e_{pl} \sim 0.03$ and $K_{pl} \sim 45$ m s$^{-1}$. A Newtonian analysis of our RVs more appropriate to the conjectured strongly interacting system will be presented in §5. The Keplerian solutions were again derived using a time of zero-mean longitude $T_0$ as the reference epoch (Sterne 1941), where the mean longitude $L = \omega + M$, and $M$ is the mean anomaly.

3.3.1 1k×1k detector

Our re-evaluation provides a significant improvement to the precision of the 222 spectra reported in Ramm et al. (see Table 2): the RMS lowers to 14.4 m s$^{-1}$ and $(\chi^2)^{1/2} = 1.02$. For the revised set of 225 RVs (having rejected the 18 suspect observations described in §2.2.1), the RMS lowers further to 10.6 m s$^{-1}$ (even though the dataset’s time-span is extended by 233 days by the additional 21 spectra obtained in 2007). These results give further justification for the rejected spectra even though they were never tested for outlier status. A plot of the corresponding RV curve and residuals is given in Fig. 4. This is the lowest orbital RMS derived for CCF RVs obtained with HERCULES, which previously was limited to about 15 m s$^{-1}$ for sharp-lined spectra (see e.g. Skuljan, Ramm & Hearnshaw 2004; Ramm 2008), and for the first time approaches the spectrograph’s design specification for CCF RVs (10 m s$^{-1}$; Hearnshaw et al. 2002).

3.3.2 4k×4k detector

A plot of the conjectured planet’s RVs, the solution’s best-fitting curve and the velocity residuals are given in Fig. 5. Besides confirming the existence of the originally reported \sim 415 day RV signal, the residuals of the 32 I$_2$-calibrated CCF RVs have relative accuracies that are uniformly similar to those solely derived from the iodine lines and AUSTRAL. Furthermore, the earliest two RVs, near JD 245 4024, have large errors and make no significant contribution to the orbital solution. Their high relative accuracy to the final fit with and without them is further vindication for the method used to derive these CCF RVs. The RVs and errors allowed a solution with an RMS of 6.5 m s$^{-1}$ and $(\chi^2)^{1/2} = 1.83$. If a further jitter of 5 m s$^{-1}$ is added in quadrature to the internal errors of all 1212 RVs the total jitter is about 6 m s$^{-1}$, a suitable value proposed by Johnson et al. (2010) for stars similar to \nu Oct, and $(\chi^2)^{1/2} = 1.06$ is derived.

4 NON-RV SPECTRAL ANALYSES

Before describing the results of our dynamical orbital analyses we next present our evidence re-affirming that this periodic RV signal is unlikely to have a stellar origin. The investigations include those for chromospheric activity using the Ca II H line, line-depth ratios and CCF bisectors, sampling respectively short, long and medium wavelengths.

4.1 Ca II H&K spectra

The vast majority of the spectra taken with both CCDs either did not include the Ca II H&K orders, or did so with very inadequate $S/N$. Only one Ca II spectrum was acquired with the
1k×1k detector owing to the need to manually move the detector to record these lines—time consuming and not ideal for obtaining precise RVs. Negligible chromospheric activity has been reported by Warner (1969) for spectra obtained during 1964-1965, whose eye-estimate value was '1' (the scale was 0–8 with 0 indicating absence of K-line emission).

With the 4k×4k CCD, RV exposures were far too short to provide adequate S/N for the Ca II lines. Therefore seventeen longer exposures were taken at irregular intervals approximately consistent with the conjectured planet’s RV cycle to monitor potential variability. Whilst our sample is relatively small, neither the H nor the K line shows any significant variability or any periodicity consistent with the RV behaviour. The K line was less well exposed and so we restrict our attention to the H line.

We followed the general method of Santos et al. (2000). We measured the total flux of a 1 Å wide window centered on the Ca II H line (λvac = 3969.50 Å) and divided this by the total flux in a second region 15 Å wide centered at 3990 Å. An overlay of the seventeen spectra in the vicinity of the Ca II H line is given in Fig. 6 after Doppler shifting has been taken into account. The S/N estimated at the centre of the order including the H line varied considerably, having an average S/N >> 96 ± 25. There was no correlation between S/N and the chromospheric-activity index SHERC. The error ε for each ratio was estimated at 10 percent for S/N = 100, and then scaled accordingly: hence

$$\varepsilon_{\text{SHERC}} = 10 \times \frac{S_{\text{HERC}}}{S/N}.$$  

The distribution of H-line ratios is given in Fig. 7. A Lomb-Scargle periodogram analysis was conducted and no periodicities significantly exceeding the background noise were found at any frequency, in particular at the RV-perturbation period ~ 415 days, nor at the estimated rotation period of ν Oct A, Prot ~ 140 ± 35 days (based on its radius, $v \sin i$ and making the simple but perhaps inaccurate assumption $i_{\text{rot}} = i_{\text{sin}}$).

4.2 Line-depth ratios

Line-depth ratios (LDRs) have a long but infrequent history for supporting or discrediting exoplanet discoveries e.g. 51 Peg (see e.g. Gray 1997; Hatzes, Cochran & Bakker 1998). In a recent paper Ramm (2015) likewise investigated the 215 ν Oct spectra reported in Ramm et al. (2009), deriving 22 LDRs from ten spectral lines in the wavelength region 6230–6260 Å. Spectra of 20 similarly evolved stars were also used to create a temperature scale. Ramm recovered the original 21 stellar temperatures with an accuracy and standard deviation of 45 ± 25 K and found no significant periodic behaviour in any of the LDRs.

Carefully constructed ratios are known to be extremely sensitive to temperature (see e.g. Gray & Johanson 1991; Gray & Brown 2001; Kovtyukh et al. 2003). Besides having no periodic behaviour, the 215 LDR-calibrated temperatures $T_{\text{ratio}}$ had a standard deviation of only 4.2 K over the several years 2001–2007. Making the realistic assumption ν Oct A was therefore not likely to be pulsating, the temperatures were converted to magnitude differences $\Delta m$ using the Stefan-Boltzmann law. The distribution of these have a striking similarity to the scatter recorded in the Hipparcos photometry obtained about 15 years previously. We now extend this LDR analysis to the newer spectra.

Unfortunately all of the LDR spectral lines utilised in Ramm (2015) occur in order $n = 91$, which, for the vast majority of our 4k×4k spectra are swamped with iodine lines. However, 47 spectra were acquired without the iodine cell (some accidentally, some intentionally) on 21 nights during twelve observing runs spanning 2538 days (Oct 2006–Sept 2013), a useful additional sample. In order $n = 91$, thirty-nine spectra have a mean $S/N = 246 ± 62$ and for the remaining eight it is $525 ± 46$, the latter being part of the set of longer exposures for acquiring our Ca II spectra. Once again, from a Lomb-Scargle analysis, there is no periodic behaviour in this latest sample in the vicinity of the ~ 415 day RV signal, none consistently across all of the 22 ratios, and none with power significantly greater than any periodogram’s background noise.

Converting each ratio into a temperature using calibration stars allows the temperature to be derived more precisely by the averaging of all the results for each spectrum. These in turn can be converted to magnitude differences that can further act as a guide for assessing the reliability of the method. The average temperature for all 22 ratios is $4811 ± 28$ K. This is consistent with the effective temperature reported by Fuhrmann & Chini (2012; $4860 ± 40$ K). The 47 averaged temperatures have a mean of $T_{\text{E,Oct}} = 4811 ± 4.1$ K, practically identical to the value reported in Ramm (2015; $4811 ± 4.2$ K). Magnitude-differences were derived and these again have a
striking resemblance to the brightness variations recorded by Hipparcos and estimated by Ramm (2015), the three sets of $\Delta m$ values now spanning about 23 years (Fig. 5). It should be noted that our estimates for $\Delta m$ are extremely sensitive to the temperature ratio $T_{\text{ratio}}/T_{\text{Oct}}$: Varying $T_{\text{ratio}}$ by only one degree changes $\Delta m$ by about 1 mmag. Such similar behaviour of three high-precision sets of $\Delta m$ values would seem to be unlikely to be due to misguided analytical methods. It would also be surprising if, whilst much larger variations did exist, they only occurred in the years not sampled.

4.3 CCF bisectors

Spectral line bisectors (see e.g. Gray 1983; Hatzes et al. 1998; Povich et al. 2001; Gray 2005) and that of CCFs (Queloz et al. 2001; Dall et al. 2006; Baştürk et al. 2011) are both well recognised means to assess if a star’s surface dynamics and irregular features can significantly influence RVs, or to identify spectral contamination from previously unrecognised stellar companions (Wright et al. 2013). Bisectors have also been shown to vary in systematic ways with surface gravity (i.e. luminosity) and effective temperature (Gray 2005; Gray 2010; Baştürk et al. 2011) though without the extreme sensitivity that for instance line-depth ratios have for temperature.

Our bisectors were derived from 675 4k×4k spectra (acquired Dec 2010 – Dec 2013) for the 12-free orders with higher $S/N$, $n = 114 – 120$. The CCFs were created using a template spectrum with $S/N \sim 240$. Five CCF flux levels were measured, at 20, 30, 45, 60 and 75% of the CCF’s parabola-fitted peak value. We constructed two variations of commonly used bisectors, the velocity span, $V_{\text{sp}} = v_{30} - v_{75}$, and the bisector inverse slope $BIS = (v_{20} + v_{80})/2 - (v_{60} + v_{75})/2$. We found no evidence of any significant periodic behaviour for any order corresponding to the RV signal at ∼415 days from our Lomb-Scargle analyses, just as was reported in the previous CCF bisector analysis of Ramm et al. (2009). There is no correlation between the bisector values and the spectra’s $S/N$.

To illustrate our bisector results we concentrate on the BIS results. To provide them in a manner we believe is more revealing, we divided the spectra into sets defined to be separate ‘observing runs’. Each ‘run’ only included spectra with no more than 3.5 days between consecutive dates. Typical observing runs lasted about a week and were separated by 2–4 weeks, but occasionally circumstances interrupted longer runs by several days (e.g. as a result of instrument failures or adverse weather), effectively separating groups of spectra. In most cases the subsets of spectra represent true separate observing runs. About half of these subsets included eight or more spectra, and the maximum number of nights included in a single ‘observing run’ was fourteen (two runs).

We derived the mean BIS $\langle BIS \rangle$ and standard deviation for the 59 allocated ‘observing runs’. We discuss the results for $n = 114$ and $n = 118$ as these have the least variability (Fig. 8). These standard deviations, $\sigma_{\langle BIS \rangle}$, for many subsets is very low, and averages $5 \pm 3$ m s$^{-1}$, or about 5% of the total BIS range for that order. For both orders, only two spectra were rejected (their BIS values were treated as outliers as they each were about $4\sigma$ from the mean). For the ten runs that included 20 or more spectra (to a maximum of 67 spectra), $\sigma_{\langle BIS \rangle} \sim 7 \pm 2$ m s$^{-1}$, and for the two runs that extended over fourteen nights $\sigma_{\langle BIS \rangle} \sim 8$ m s$^{-1}$. The $\langle BIS \rangle$ values for these two orders have ranges significantly less than the RV signal’s amplitude and are only weakly correlated ($r = 0.36$), whereas the 675 RVs are perfectly correlated ($r = 1.00$). Thus we claim that most of the scatter is not due to measurement errors, otherwise, firstly, the scatter would presumably be evident in the individual runs. Since our spectra can easily reveal the signal in our CCF RVs ($K_{\text{vel}} \sim 40 – 45$ m s$^{-1}$), we also claim these very small ‘observing run’ standard deviations imply we should be able to easily detect the perturbation signal in our CCF bisectors if it was present. The distribution of BIS mean values seems more likely to be due to acquisition variations, a result of the reduction process and/or stellar variability unrelated to the RV signal.

7 This low fraction, a few percent, is true for all seven orders.
5 DYNAMICAL ORBITAL SOLUTIONS

We derived dynamical orbital solutions for the 225 1k×1k detector RVs and the full set of 1437 RVs, the latter being the global solution we desire for our stability modelling. We characterize the masses and orbits of the ν Oct components using an N-body differential evolution Markov Chain Monte Carlo (RUNDMC, Nelson et al. 2014a), which incorporates the Swarm-NG framework to integrate planetary systems on GPUs (Dindar et al. 2013). We adopt our prior probability distribution and likelihood function from Nelson et al. (2014a). A Bulirsch-Stoer integrator, similarly used by Go¨ zdziewski (2016 RAS, MNRAS) and its coordinate-system variant of the general Bulirsch-Stoer (B-S) integrator (Nelson et al. 2014a; Nelson et al. 2016). On one hand, ν Oct has a much lower dimensional model (i.e. only three bodies and fewer orbital parameters); on the other hand, the proximity of these masses suggests the presence of extremely strong gravitational interactions, which can result in a posterior distribution that is very difficult to sample from.

Considering the lessons from Nelson et al. (2014a) regarding how to explore parameter space efficiently, we set the following algorithmic parameters for RUNDMC: \( n_{\text{chains}} = 300, \sigma_1 = 0.01, \) and MassScaleFactor=1.0. We set our integration step to roughly 84 minutes and use the time-symmetrized Hermite integrator (Kokubo et al. 1998). The epoch of these solutions is the time of the first observation, i.e. JD245 2068.0607 for each dataset.

We sampled from the Markov chains after they had burned-in sufficiently and obtained a set of posterior samples. For the RVs acquired only with the 1k×1k detector, summary statistics of the model parameters are given in Table 5 and corresponds to \( (\chi^2)^{1/2} = 0.85. \) A similar table for the total set of RVs is given in Table 2 and has \( (\chi^2)^{1/2} = 0.99. \)

6 STABILITY MODELLING

Our posterior models were integrated for 10\(^6\) years using a Jacobi-coordinate-system variant of the general Bulirsch-Stoer (B-S) integrator in the N-body dynamics package MERCURY (Chambers 1999). A Bulirsch-Stoer integrator, similarly used by Goździewski et al. (2013) in their detailed analysis of the ν Oct system, is appropriate given the assumed geometry includes a nearby massive secondary-star perturber, and which makes for instance the ‘hybrid’ integrator unsuitable. Nothing remained dynamically stable past our integration baseline.

6.1 Grid search for stable models: methods and results

Given the lack of promising results with our posterior samples, a grid search was also undertaken. The grid was created from the planet best-fitting planet elements \( a, e, i, \omega, \) and \( M, \) encompassing ±3\( \sigma \) across a uniformly divided range for each. Since...
Table 8. The single model found to survive $10^8$ years within 1-sigma of our dynamical solution’s best fit (given in Table 4). The component masses were $M_1 = 1.01 M_\odot, M_2 = 0.58522 M_\odot$ and $M_{pl} = 0.00201 M_\odot = 2.1 M_{Jup}$.

| companion | $a$ (au) | $e$ | $i$ (°) | $\omega$ (°) | $\Omega$ (°) | $M$ (°) |
|-----------|---------|-----|---------|-------------|-------------|--------|
| $\nu$ Oct B | 2.62959 | 0.2368 | 70.8 | 75.0 | 87.0 | 339.3 |
| planet | 1.27261 | 0.12 | 115.0 | 355.0 | 237.8 | 315.0 |

$\Omega_{pl}$ was relatively precise compared to the other orbit angles, it was also kept constant. The grid was composed of $9 \times 15 \times 13 \times 11 \times 10 = 193,050$ models, the respective grid steps were $\Delta a_{pl} = 0.00412$ au, $\Delta e_{pl} = 0.015$, $\Delta i_{pl} = 1^\circ$, $\Delta \omega_{pl} = 10^\circ$, $\Delta M_{pl} = 10^\circ$. The binary elements, which have relatively very high precision, were kept constant at their best-fitting values.

Given the models’ exceptional geometry the choice of a reliable time-step $\tau$ was also given careful consideration. Ultimately it was decided a suitable strategy was to process the entire grid for several time-steps. Small but, critically, insignificant survival-time differences for each model would give us confidence the integrator was likely to be reliable for this extreme system. The shortest time-step was relatively brief, 0.4 days ($\sim 10^{-3} P_{pl}$), and the three others were simply prime numbers 3, 7 and 11 days, these chosen to be integers and non-integer multiples of any other. Finally, for the two boundary time-steps 0.4 and 11 days, we extended our integration times to $10^8$ yrs. The resulting survival times were indeed very similar.

The time-step chosen for the grid results reported here, $\tau = 11$ days, was therefore not at all apparently critical, but being less CPU-time demanding, it was the only time-step that had its maximum integration time extended further, for all models to $10^7$ years. The model did not survive if the planet 1. travelled beyond 5 au (about twice $a_{bin}$: 89% of the models), 2. collided with the central/primary star (5%), or 3. collided with the secondary (0.3%). Thus about 5% of our grid models (9,786 models) survived to $10^7$ years. Most of the grid parameters (i.e. $a_{pl}, e_{pl}, i_{pl}, M_{pl}$) have gently sloping distributions across their entire ranges for the fraction of survivors to $10^7$ years. The mean longitude $L = \omega + M$ distribution differed in that it was strikingly symmetric and narrow. This symmetry gave us further confidence our B-S integrator was reliable. The fraction of models surviving to $10^5$, $10^6$ and $10^7$ years are illustrated in Fig. 10. The models most likely to survive, even to $10^7$ years, had initial $L_{pl} = 310 \pm 10^\circ$.

The distribution of stable models with respect to the planet’s initial eccentricity and mean longitude is included in Fig. 11. We find higher eccentricities tend to produce more stable models. One model that survived to $10^7$ years had grid values all within 1-sigma of the best-fitting elements. Due to our computer-time limitations, only this one had the integration time extended to a little beyond $10^8$ years. One model survived the full integration for two time-steps, 0.4 and 11 days, but the planet was ejected at 35 and 91 Myrs for the 3-day and 7-day time-steps respectively. This model’s parameter set is given in Table 8.

8 For instance, for the four time-steps, the mean number of survivors to $10^4$ yrs was 35, 351 ± 24 and to $10^5$ yrs it was 17, 334 ± 52. The survival times for the individual models were within 5% of each other in nearly 85% of them.

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**Figure 10.** Histogram of the full grid of initial mean longitudes $L$ for our 193,050 stability models with a time-step of 11 days. The lightly hatched subset survived to $10^7$ years (35,327 models), the double hatched to $10^8$ yrs (17,281 models), and the bold to $10^9$ years (9,786 models). $L > 360^\circ$ has been plotted to more easily illustrate the distributions.

**Figure 11.** Grid search results in planet mean longitude and eccentricity space. Darker shades represent a higher fraction of stable systems residing within that particular cell (color scale on right). Black dots are posterior samples. The online version is in colour.

7 OTHER CONSIDERATIONS

The controversial $\sim 415$-day RV signal demands every possible characteristic of $\nu$ Oct be considered. Here we discuss the system’s space velocities, future imaging and astrometry, and the nature of the conjectured planet’s discovery.

7.1 Space velocities and age estimate

The conjectured $\nu$ Oct planet poses a challenge with regards its formation and some dynamical process such as a gravitational event including a passing star would appear to be amongst the most likely. Hence it seems worthwhile to determine $\nu$ Oct’s present space velocities, although these results presumably place only a weak constraint on any past event. Quite reliable estimates should be achievable given the recent updating of all the required parameters. Space velocities inconsistent with the estimated age might imply such a
The conjectured $\nu$ Oct retrograde planet

7.2 Future astrometry and imaging

Any dynamical orbital solutions, stability studies and efforts to understand the possible formation scenarios will also be able to be conducted with greater confidence if $\nu$ Oct’s stellar masses and astrometry are more accurately determined. Ideally, this should be done in an as model-free manner as possible. Direct imaging and astrometric observations would also help define the true nature of $\nu$ Oct B since the contrast observed would determine if it was a late-type main-sequence star or a white dwarf (WD). Assuming the stellar components are coeval, if $\nu$ Oct B is found to be a WD, which presumably could also reveal itself by a UV excess, it would have had to evolve much faster than the present primary, shedding at least one solar mass in the process (the mass difference of the present stellar components).

Since an astrometric orbit for the binary of reasonable quality has now been determined, in principle, the stellar masses can be derived by a single astrometric observation (the angular separation $\rho$ and the position angle $\theta$). One such interferometric observation was reported several decades ago. Unfortunately, whilst Morgan, Beckmann & Scaddan (1980) claimed success with their single observation ($\rho = 0.0104$, $\theta = 331^\circ$), and their separation is approximately consistent with our prediction ($\rho \sim 0.12$), their position angle is not, since we derive $\theta \sim 272^\circ$, thus making their claim questionable. The predicted angular separation has just passed a minimum and will achieve its next maximum in September 2016 (Fig. 12). Modern instruments should be able to make the necessary observations, particularly if $\nu$ Oct B is a high-contrast main-sequence star. Our derived mass for the secondary star, if it is unchanged, corresponds to a late-K or early-M dwarf having $M_V \sim 8 - 9$ mag, thus $\nu$ Oct B may be only six magnitudes or so fainter than $\nu$ Oct A. A large series of astrometric observations would help better define the entire AB orbit, including for instance $\Omega_{\text{bin}}$, which we fixed for our dynamical analyses but may be more inaccurate than we suppose. Finally, such observations may also reveal any previously unknown stellar companions, such as the hierarchical triple scenario proposed by Morais & Correia (2012).

8 DISCUSSION

This work demonstrates that the extraordinary retrograde planet in $\nu$ Octantis, whilst not yet definitively proven, remains the most credible of the known possible scenarios for the RV signal first described by Ramm (2004). Credibility for the planet now arises primarily from several independent high-precision observational methodologies.

The first evidence is the RV signal itself, now demonstrated to be persistent for nearly 13 years (2001–2013), and using different methods.

7.3 Serendipity

The HERCULES spectrograph is clearly capable of providing high-precision RVs and has been in service for 15 years, yet the $\nu$ Oct planet is the only one so strongly proposed from its spectra. What are the chances such an extraordinary planet could be discovered in these circumstances? One would imagine they would be very slim indeed. So we ask, just as Wright et al. (2013) queried their discovery of the near face-on binary in MARVELS-1, how can we make the proposed discovery somewhat more plausible? In the first instance, given the Mt. John telescope’s relatively small aperture (1-metre), any planet-hunting program is seriously disadvantaged as compared to those using much larger apertures in more favourable observing sites. Consequently, such programs have rarely been attempted at Mt. John (but see Murdoch, Hearnshaw & Clark 1993). Instead many HERCULES-based projects study, for instance, pulsating stars and binaries with relatively short periods (often less than that of $\nu$ Oct). These are not ideal or typical targets for planet hunting. However $\nu$ Oct is a suitable object for assessing HERCULES’s long-term RV precision, being a very bright, sharp-spectral-lined SB1 (and previously having a low-precision orbital solution), is easily circumpolar at Mt. John, and was known to be a very constant star. Hence it was included in the first HERCULES project (Ramm 2004). The ~ 415 day RV signal was then easily found once it was adequately observed. The serendipitous discovery was aided by its far southern declination making $\nu$ Oct less easily observed at many other facilities (though it was initially included in the Pan-Pacific Planet Search; Wittenmyer et al. 2011). The remaining surprise may then be limited to the fact that something which is presently exceptional and so presumably quite rare, is so relatively nearby.

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9 $\gamma = +35.24 \pm 0.02$ km s$^{-1}$; $\varpi = 45.25 \pm 0.25$ mas; $\mu_\alpha \cos \delta = +52.58 \pm 0.53$ mas/yr; $\mu_\delta = -240.80 \pm 0.47$ mas/yr; note the correction to the sign of $\mu_\delta$ given in Ramm et al..
strategies for deriving the RVs (CCFs and I$_2$ lines). The RMS of our solution for all 1437 RVs is 8 m s$^{-1}$ with ($\sigma^2$)$^{1/2}$ = 0.99 (see §5). Similar but better long-term RV precision has been achieved with the single stars $\beta$ Pav and $\tau$ Cet during the parallel observing campaign mentioned in §4.2. For instance, the RVs from observations of $\tau$ Cet ($N = 1377$) acquired over nearly six years (2008–2014), have an RMS of 4.6 m s$^{-1}$, and the median single-night RMS ($N \geq 10$ per night) is 2.7 m s$^{-1}$ (Bergmann 2015). Hence the signal cannot be due to instrument errors or the like – for instance it is also not present in RVs derived for the similar SB1 $\beta$ Reticuli (K2IIb) studied in nearly identical circumstances from 2001–2007 (Ramm 2004; Ramm et al. 2009).

As well as our large new dataset of high-precision RVs, the favourable revision of the previously published CCF RVs is expected to have been helpful for our dynamical orbit and stability modelling and for future studies. The orbits derived are consistent with those reported by Ramm et al., at least with regards the observer-independent elements $a$, $e$, and $P$. These three elements are at the heart of the controversial claim for the $\nu$ Oct planet since they place its orbit, on average, midway between the stellar components having $a_{\text{min}} \sim 2.6$ au.

8.1 Luminosity class of $\nu$ Oct A

The primary star of $\nu$ Oct is somewhat evolved from the main sequence but we wonder if it truly is a giant as is typically claimed i.e. K0III (e.g. ESA 1997) or K1III (e.g. Gray et al. 2006), and already questioned by Ramm (2015). Cool giants are known to have cyclic RV variability periods of the order of hundreds of days and RV amplitudes of 50 – 600 m s$^{-1}$ (Walker et al. 1989; Hatzes & Cochran 1998; Cummings 1998). Cool subgiants, whilst less well understood in terms of surface dynamics (Hatzes et al. 2003), are generally less dynamically active than true giants, so the luminosity class of $\nu$ Oct A has some significance. The absolute magnitude of $\nu$ Oct A ($M_V = +2.02$) is maybe as much as two magnitudes fainter than MK-type normal giants of luminosity class III, the latter having their locus bounded more or less by $-1.5 \leq M_V \leq +0.5$. The absolute magnitude and spectral type suggest $\nu$ Oct A is instead no more evolved than luminosity class IIIb - IV (see fig. 1 Keenan & Barnbaum 1999). Also, as well as having many other characteristics similar to $\nu$ Oct A, the planet-hosting $\gamma$ Cep A has $M_V$ only 0.5 mag less, and is now classified K1IV (Fuhrmann 2004). If a re-classification of $\nu$ Oct A is valid, just as was later realised for $\gamma$ Cep A, our present understanding of such less evolved stars is another reason why significant surface dynamics would seem less likely (Hatzes et al. 2003; Walker 2012).

8.2 Surface dynamics

Regardless of $\nu$ Oct A’s true luminosity class, no evidence consistent with any kind of significant surface dynamics has been found over several decades and at multiple wavelengths e.g. in radio (Beasley, Stewart & Carter 1992), microwave (Slee et al. 1989), visible (Hipparcos 1992), and X-rays (Hünsch et al. 1996), and for Ca II emission (Warner 1969; Ramm et al. 2009). Pérez Martínez, Schröder & Cuntz (2011) identify $\nu$ Oct A as having a Mg $h + k$ chromospheric emission-line surface flux very close to their empirically derived basal flux of their sample of 177 cool giants. Our investigations of Ca II H-line emission, CCF bisectors and line-depth ratios are also all consistent with the primary star having negligible dynamical surface behaviour. The LDR and bisector results challenge any possibility that surface-activity cycles or pulsations are the cause: both here and in Ramm (2015) the extremely temperature-sensitive LDRs converted to magnitude differences $\Delta m$ strikingly mimic the Hipparcos photometric variations. Furthermore, the predicted spot-filling factor $f_{\text{sp}} \sim 1\%$ from the $\Delta m$ values (see Ramm 2015, fig. 10) can be used to estimate the corresponding RV amplitude (see Hatzes 2002). Whilst the predictions of Hatzes were based on solar-type stars, since they were apparently applicable for the study of other non-solar-type stars e.g. HD 13189 (K2 II; Hatzes et al. 2005), we claim they are equally valid here. The predicted amplitude ($\sim 15$ m s$^{-1}$) is about 3× smaller than that observed.

Two other details relate to the unlikely possibility of surface dynamics being involved. Firstly, as Ramm et al. (2009) first noted, if the RV signal is related to starspots, this would have to be both persistent – now extending to 12.5 years – and geometrically fortuitous to be able to produce the near-sinusoidal RV signal. Secondly, the estimated period of rotation of $\nu$ Oct A $P_{\text{rot}} \sim 140 \pm 35$ days, is about one third of the RV signal’s period. This estimate assumes $P_{\text{rot}} = P_{\text{min}}$ which is presumably less likely to be true if a significant gravitational event has been involved in this system’s history. Establishing a reliable and accurate rotational period $P_{\text{rot}}$ for the star will help decide if starspots have any remaining credibility, though the obvious challenge will be achieving this for what seems to be an unspotted and only slightly evolved star. The same arguments seem to challenge the somewhat more mysterious macroturbulent regions proposed by Hatzes & Cochran (2000) for the RV behaviour of the faster rotating Cepheid-type variable Polaris and further discussed in relation to the planet-hosting massive K-giant HD 13189 (Hatzes et al. 2005). Pulsations are also challenged by the lack of any observational evidence (e.g. no cyclic photometric or LDR-temperature variations). Finally, our Newtonian solutions repeat the finding in Ramm et al. that the orbital period of the binary and conjectured planet may be close to a simple 5:2 ratio. This would be a somewhat unexpected coincidence if the eventual cause has a stellar origin.

8.3 Hierarchical triple-star scenario

Our orbital solutions also provide new evidence against the possibility that $\nu$ Oct is instead a hierarchical stellar triple. As mentioned in the Introduction, Morais & Correia (2012) presented this as an explanation, claiming the tell-tale evidence would be aapsidal precession rate $\Delta \omega = -0.86$ yr$^{-1}$. This is not supported by any orbital solutions. We have updated $\omega_i$ from our full dynamical analysis ($\omega_i = 75.0 \pm 0.2^\circ$; Table 2). We compared this to $\omega_i$ derived from a subset of the 21 historical RVs (Campbell & Moore 1928; Jones 1928). We selected the first thirteen RVs which are confined to 1904–1911 (JD241 6640–JD241 9317) which provide a slightly more precise (and hopefully more accurate) $\omega_i$ than with all 21 RVs. We derived $\omega_i = 67.0 \pm 12^\circ$ for the zero-mean-longitude epoch JD241 7272. A single-Keplerian orbit was derived since that is all these few low-precision RVs can justify. Between this epoch and that defined in Table 2, the time of the first modern RV ($\sim$ JD245 2068), is a time-span of 95 years. The apsidal precession Morais & Correia predict over this time-span is about $-82^\circ$, which clearly is not the calculated difference between these two $\omega_i$ values. The historical RVs have very low precision, but it seems they are easily capable of disclosing such a difference if it existed.

To further test the prediction by Morais & Correia, we fitted a precessing Keplerian model to the full set of radial velocities. In this model, we fitted the secondary’s orbit as a Keplerian orbit that
is allowed to precess with time, with a precession rate of \( \dot{\omega} \). This term is not governed by any particular physical mechanism such as general relativity, a stellar quadrupole, or tidal effects. It is merely a free parameter that we will constrain from the radial velocity data.

Given the large signal-to-noise of the secondary star, we adopted uniform prior probability distributions in an arbitrarily large range for all of our model parameters (\( P, K, \omega, M, \dot{\omega}, \), etc.). We performed an affine-invariant MCMC (Foreman-Mackey et al. 2013) to sample from the posterior distribution using a likelihood function similar to as described in Nelson et al. (2014a). After burning-in sufficiently, we sampled from the Markov chains and constrained \( \dot{\omega} = +0.00051 \pm 0.00006 \) deg per year. Not only is this result two orders of magnitude off from the prediction, but it is also in the opposite direction (i.e. a prograde precession).

### 8.4 Stability modelling

Our stability studies have provided mixed results for credibility for the planet. On one hand, the observations provided very precise orbital and mass constraints for a retrograde planet model. However, none of the posterior samples were dynamically stable for 10<sup>8</sup> years. One might suggest we are actually witnessing a system on the brink of orbital destabilization, but given the time-scale of instability compared with the age of the star, this would be highly improbable. Several trial runs of the observations revealed many local minima which could easily trap our Markov chains depending on our set of initial conditions. It is possible, therefore, that our results are based on samples from a local rather than the true global minimum, which, based on the results of Goździewski et al. (2013), would not be too surprising.

The grid search revealed a region of parameter space with a higher probability of long-term stability. Only a relatively small fraction of models survived to 10<sup>7</sup> years (~ 5%). This may, however, be anticipated given the extreme nature of the system we are modelling. The majority of the stable models are somewhat distant from the best-fitting solution (see Fig. 11), but one model whose grid values are all within 1-\( \sigma \) of the best fit (see Table 8) was stable to at least 35 Myrs years for our grid’s four time-steps, and stable beyond 10<sup>8</sup> years for two of them (\( \tau = 0.4 \) and 11 days). If the conjectured system’s formation arose from a short-lived gravitational event (e.g. a passing star) the mutually inclined orbit, rather than a coplanar one, would seem to be more consistent with that possibility. A hypothesis of a moderate mutual inclination could also provide other significant advantages for more quickly resolving the true nature of the enigmatic \( \nu \) Oct system e.g. in the form of verifiable predictions for orbit evolution of the binary and/or the conjectured planet such as Kozai-like mechanisms (Kozai 1962).

### 9 CONCLUSION

To date, the observational evidence more strongly supports the retrograde planet’s reality than any other known alternative. Yet, due to its exceptional nature, definitive independent evidence is essential for deciding the fate of this controversial planet. Spectra acquired with much higher \( S/N \) and resolving power (and overall fidelity) will help decide the credibility of any stellar-origin scenarios, and additional preferably more precise RVs will better define the conjectured orbit and facilitate better predictions of its evolution. This can lead to a re-investigation of a self-consistent Newtonian model that also incorporates the Hipparcos and future astrometry. If the planet’s existence is confirmed, a theoretical explanation will be needed. A gravitational interaction with a single or multiple bodies would presumably require the least, if any, revision to our present understanding of such scenarios. Some other migration process involving the stars or their planetary companion/s may also be applicable, though as with all formation scenarios, this too would seem to be a challenging one. If these options proved not to be viable, then \( \nu \) Oct would instead aggressively confront our present understanding of coeval planet formation in such tight binaries, regardless of the system’s original configuration. For many, the latter would be a very difficult scenario to believe. It is perhaps, however, prudent to recall that not so long ago (the 1980s and even early 1990s) it would have been almost as hard to believe hot-Jupiter exoplanets existed either, or indeed that there was any sense looking for exoplanets anywhere (Walker 2012).

Evidence against the planet should be as equally robust as evidence for it, since, if it is real but wrongly dismissed, we would presumably lose or at least delay our many opportunities for the study of its unique characteristics. If the planet is non-existent, but all the astrometric, spectroscopic and photometric evidence is accurate, the consequences quite likely exceed that arising from the planet’s reality. We would have to acknowledge there is a new variation of stellar behaviour or orbit-related process that is consistent with all the current evidence. Such a discovery would have far-reaching consequences, both as a discovery in itself, but as a significant challenge to the existence of many other already and yet-to-be claimed RV-detected planets, perhaps regardless of the host star’s evolution.

### 10 ACKNOWLEDGEMENTS

The Mt John programme was generously funded by Marsden Grant UOC 1007 administered by the Royal Society of New Zealand. The project was also supported in part by the Australian Research Council Discovery Grant DP110101007 (RW & FG). The authors thank McDonald Observatory, University of Texas at Austin for sharing the Sandiford iodine cell. The authors acknowledge the contribution of the New Zealand computer and analytics services NESI (New Zealand eScience Infrastructure), funded jointly by NeSI’s collaborator institutions and through the Ministry of Business, Innovation and Employment (URL http://www.nesi.org.nz). DJR thanks François Bissey for his support using these High-Performance Computing facilities at UC. We thank Stuart Barnes for his enthusiasm establishing the early work of this iodine-cell campaign and Jovan Skuljan for reconfiguring his reduction software HRSP for the larger 4k×4k detector. BEN thanks Eric Ford, Jason Wright, and Trifon Trifonov for useful conversations about various interpretations of the data. DJR also thanks Gerald Handler for helpful discussions relating to pulsating stars, Trifon Trifonov for identifying a data anomaly and other useful comments, and Aleksandra Jarmolik for many helpful discussions including, on the lighter side, her recommendation to read Stanisław Lem’s “Solaris”, which seems related to this work on several levels. We also

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10 See e.g. Fischer et al. (2016) for the state-of-the-art of RV precision and its future goals and challenges. The work of Wright & Eastman (2014) identifies one avenue of review of our RVs based on the barycentric corrections, which we have no reason to suspect are significantly inaccurate, but which we have provided for this purpose.
appreciated the support of all staff at the Mt. John Observatory. Our work has benefited from the databases provided by SIMBAD, VizieR (CDS, France) and the NASA ADS.

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