The Age of the Carina Young Association and Potential Membership of HD 95086

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ABSTRACT
Carina is a nearby young stellar association. So far, only a small number of stars have been clearly identified as members of this association. In this paper we reanalyse the membership of the association in light of Gaia DR2 data, in particular finding that HD 95086 is a potential member (probability of 71%). This star is noteworthy as one of the few stars that hosts both a detected debris disc and a directly imaged planet. It has previously only been considered as a potential member of the Lower Centaurus Crux (LCC) – part of the Scorpius-Centaurus association. We also reanalyse the age of the Carina association. Using a Bayesian inference code applied to infer a solution from stellar evolution models for the most probable (>99%) members of Carina, we infer an age for the association of 13.3+1.1−0.6 Myr, much younger than previous studies. Whilst we have revised HD 95086’s association membership from LCC to Carina, the fact that we also find Carina to have a younger age, similar to that of LCC, means that the estimates of HD 95086b’s mass remain unchanged. However, the younger age of Carina does mean that the companion to another Carina member, HD 44627 (or AB Pic), has a mass that is more clearly in the planet rather than brown dwarf range.

Key words: stars: individual: HD 95086 – stars: kinematics and dynamics – open clusters and associations: general – planetary systems – circumstellar matter – stars: evolution

1 INTRODUCTION
There are a number of methods for determining the age of a star. These include using gyrochronology, X-ray emission, lithium depletion, chromospheric activity and stellar evolution models. Not all methods work equally well for all spectral types and evolution phases, and the accuracy for an individual star is usually not high (see e.g. Vican 2012).

However, most stars are thought to form in clusters that slowly disperse into associations (e.g. Ambartsumian 1947; Blaauw 1964) before dispersing completely into the Galactic field. When an association of stars is identified, then its age can be determined more accurately by assuming all the stars are coeval.

Based on a survey of X-ray sources in the southern hemisphere and kinematic information from Hipparcos, Torres et al. (2001) identified the existence of the Great Austral Young Association. Further study of this association by Torres et al. (2008), demonstrated that it should be subdivided into at least three young associations: Tucana-Horologium (Tuc-Hor), Columba and Carina. These are expected to be related and likely of a similar age, but are distinguished by their velocity components. Whilst Tuc-Hor is compact and well defined, the Columba and Carina associations are more diffuse and their membership is debated. This is particularly true of Carina, with, for example, only 7 bona fide members listed by Gagné et al. (2018a) compared to 20 and 45 bona fide members for Columba and Tuc-Hor respectively.

In this paper we reconsider the membership of the Carina association in section 2 based on the Gaia DR2 data. In doing so, we propose that HD 95086 is a potential Carina member for the first time. The age of this star is of particular interest as it hosts both a directly imaged planet and a resolved debris disc. In section 3 we then reconsider the age of the association, first by comparing stellar evolution models to the Gaia photometry and then by considering the kinematic evolution of the association. We conclude in section 4 by discussing the implications of these findings.

2 CARINA MEMBERSHIP
Stellar associations were first determined by finding stars that are close together on the sky, are at a similar distance and moving in a similar direction. For nearby associations, the stars typically spread across the sky and can be mistaken for
foreground stars, so it is necessary to consider their Galactic coordinates, XYZ, and space velocities, UVW (e.g. see the reviews by Zuckerman & Song 2004; Torres et al. 2008). Various methods have been developed to do this, which are described in detail by Riedel et al. (2017). For our purposes we shall use the BANYAN Σ code (Gagné et al. 2018a) to determine association membership as this is the most comprehensive code available, including 27 young associations out to a distance of 150 pc. BANYAN (Bayesian Analysis for Nearby Young AssociationS) is an algorithm based on Bayesian inference, where associations are modeled with uni-dimensional Gaussian distributions in Galactic coordinates XYZ and space velocities UVW originally developed by Malo et al. (2013). This was further improved to model associations as freely rotating three-dimensional Gaussian ellipsoids in position and velocity space for BANYAN II (Gagné et al. 2014). BANYAN Σ works with updated and new models of young associations and uses full six-dimensional multivariate Gaussians in position and velocity space. In order to use this code, a minimum of the celestial coordinates and proper motions are required, but parallaxes and radial velocities (RVs) can also be provided to further constrain the results.

Malo et al. (2013); Moór et al. (2013a); Malo et al. (2014); Elliott et al. (2015); Silverberg et al. (2016); Gagné et al. (2018a,b); Gagné & Faherty (2018); Schneider et al. (2019) have all suggested various stars as members of Carina. We compile an initial list from these papers, but first need to determine the membership probability using the latest position and velocity data. In order to do this we cross match the stellar coordinates of each of the potential members with the Gaia database to determine their Gaia DR2 ID and retrieve their coordinates, parallaxes, proper motions and (where available) RVs.

As Gaia DR2 does not include RVs for all stars, for a number of stars we used RVs from an alternative source. Note that in the case of spectroscopic binaries, care must be taken as the RV can vary strongly as stars orbit each other. In our sample, two stars are listed in the Washington Double Star Catalog (Mason et al. 2001): HD 83096 and AL 442. The RV for HD 83096 was measured by 

\[ v_r = 19.33 \pm 0.29 \text{ km s}^{-1} \]

and \[ v_r = 19.54 \pm 0.26 \text{ km s}^{-1} \]. Neither of these is far enough from the Schneider et al. (2019) measurement to affect our results.

The six-dimensional position and velocity information was then passed to BANYAN Σ to check the association membership probabilities of these stars. The stars that are found to have a membership probability >50% are presented in Table 1 along with their source IDs and radial velocities.

| Name          | Gaia DR2 ID   | \( v_r \) km, s\(^{-1} \) | \( v_r \) source                  | Prob. (%) |
|---------------|---------------|--------------------------|----------------------------------|-----------|
| HD 94855      | 526567067229279260 | 20.48±0.27               | (Gaia Collaboration et al. 2018) | 100.0     |
| UCAC3 53-40215 | 529710067744079872 | 21.17±0.41               | (Schneider et al. 2019)         | 100.0     |
| 2MASS J08040543-6316396 | 527746202917606400 | 22.0±0.85                | (Schneider et al. 2019)         | 100.0     |
| 2MASS J09315840-6209258 | 525098886473323512 | 19.21±1.24               | (Schneider et al. 2019)         | 99.9      |
| HD 42270      | 462130581745761876 | 16.7±0.6                 | (Torres et al. 2006)            | 99.9      |
| 2MASS J08063608-7444249 | 521393451458791230 | 17.0±1.04                | (Gaia Collaboration et al. 2018) | 99.7      |
| HD 37402      | 475944478617588584 | 23.7±0.05                | (Gontcharov 2006)               | 99.7      |
| HD 298936     | 553671341378999063 | 18.4±0.44                | (Gaia Collaboration et al. 2018) | 99.6      |
| m Car         | 525109859320122137 | 20.0±4.0                 | (Gontcharov 2006)               | 99.6      |
| 2MASS J06262199-7516404 | 526154496328279552 | 16.45±2.18               | (Gaia Collaboration et al. 2018) | 99.4      |
| V479 Car      | 529914154145254528 | 19.26±0.92               | (Schneider et al. 2019)         | 99.3      |
| HD 44627      | 549505259669570816 | 21.86±0.37               | (Gaia Collaboration et al. 2018) | 98.9      |
| HD 55279      | 5208216951043669216| 16.44±0.45               | (Gaia Collaboration et al. 2018) | 98.7      |
| AL 442        | 5266182443853174784| 20.96±1.15               | (Schneider et al. 2019)         | 97.7      |
| 2MASS J07441105-6485052 | 5287415735666649728 | 19.9±2.7                 | (Gaia Collaboration et al. 2018) | 96.9      |
| 2MASS J09180165-5452332 | 531060627025187456 | 25.43±3.12               | (Schneider et al. 2019)         | 96.9      |
| HD 83096      | 549505259669570816 | 21.86±0.37               | (Gaia Collaboration et al. 2018) | 98.9      |
| 2MASS J07065772-5353463 | 5491506843495850240 | 22.57±0.9                | (Schneider et al. 2019)         | 96.2      |
| WISE J080822.18-644357.3 | 527709609746882560 | 22.7±0.5                 | (Murphy et al. 2018)            | 95.1      |
| 2MASS J07053788-6263059 | 5286700525517035768 | 22.57±0.72               | (Schneider et al. 2019)         | 94.6      |
| TYC 8602-718-1 | 5308164516541067648| 22.65±1.4                | (Gaia Collaboration et al. 2018) | 94.4      |
| HD 83096      | 5217846851839896704| 22.44±0.78               | (Gaia Collaboration et al. 2018) | 93.6      |
| ion Hyi       | 462684378944938880 | 14.6±0.21                | (Gaia Collaboration et al. 2018) | 89.6      |
| 2MASS J04082685-7844471 | 4625883599760005760 | 14.25±0.86               | (Gaia Collaboration et al. 2018) | 86.3      |
| 2MASS J08194309-7401232 | 5219983787046519168 | 26.24±1.54               | (Schneider et al. 2019)         | 82.7      |
| HD 95086      | 5231963962676292224| 17.0±2.0                 | (Moór et al. 2013b)             | 70.8      |
| TYC 9200-446-1 | 5219351911459314048| 18.0±1.48                | (Gaia Collaboration et al. 2018) | 57.5      |

Table 1. HD 95086 and potential members of Carina (as identified in section 2 and ordered by their membership probability) with their radial velocities, radial velocity source and probability of membership as determined by BANYAN Σ.

2.1 HD 95086

HD 95086 is a pre-main sequence star of spectral type A8 at a distance of 86.2±0.3 pc (Bailer-Jones et al. 2018). It is one of the few systems with both a directly imaged planet (Rameau et al. 2013) and a debris disc (Chen et al. 2012). Precisely determining the age is necessary to infer the mass of the planet. It also helps us place the system in the context...
of the collisional evolution of debris discs (e.g. Krivov et al. 2018; Krivov & Booth 2018).

de Zeeuw et al. (1999) proposed that the star could be part of the Lower Centaurus Crux (LCC) – a sub-region of the Scorpius-Centaurus Association – based on Hipparcos data, although they only gave it a probability of 41%. Rizzuto et al. (2012) also included it as a member of LCC but with a higher probability of 81%. In their case, this high value is because they interpreted the presence of a debris disc as a proxy for youth and, thus, increased the prior. Damiani et al. (2019) included it in the diffuse population of LCC, although they noted that a 10-30% contamination rate due to the method used is expected. So far, however, no publication has considered the possibility that it is a member of a different association. Due to questions about its RV, particularly in relation to the possible presence of CO gas in its debris disc (Booth et al. 2019), we have reason to question its association membership.

As HD 95086 has an effective temperature >7000 K (the exact temperature is inferred along with the age in subsection 3.1 and can be found in Table B1), its RV was not determined for the Gaia DR2, for which RVs could only be accurately determined for stars in the effective temperature range 3500-7000 K (Sartoretti et al. 2018). However, two values for the RV of HD 95086 do exist in the literature. Madsen et al. (2002) used the Hipparcos data together with the assumption that it is a member of LCC to estimate that it should have an RV of 10.1±1.2 km s\(^{-1}\). In a similar manner we can use the Gaia DR2 data with Banyan \(\Sigma\) to revise this prediction of the expected RV. We find that the probability of HD 95086 being in LCC is 33.8% and, if it is in this association, it should have an RV of 15.9±3.7 km s\(^{-1}\), which is higher than the value from Madsen et al. (2002). In addition, there is a probability of 48.5% that the star is actually a member of the Carina association and, in that case, the RV would be 17.1±0.6 km s\(^{-1}\).

Moör et al. (2013b) spectroscopically measured the RV\(^1\) to be 17±2 km s\(^{-1}\). This perfectly matches the value expected if this is a Carina member and so, when we include this value of the RV as an input when running BANYAN \(\Sigma\) we find that the probability of this star being in LCC drops to 23.8% whereas the probability of it being in Carina rises to 70.8%. This is further illustrated in Figure 1, which shows HD 95086 on the outskirts of Carina with regards to its position and with a velocity vector that is very close to that of the Carina model.

In addition to checking how the present day position and velocity of HD 95086 compares to the known young associations, we can also trace back the star’s position and association distributions to determine how close they were in the past. To study the Galactocentric motion of HD 95086, Carina and LCC we make use of the code described in Neuhäuser et al. (2019), which computes the orbits by a numerical integration of their equations of motion as defined by the Galaxy gravitational potential consisting of a three compo-

\(^1\) The spectroscopic catalogue of Kharchenko et al. (2007) also includes HD 95086 and lists the radial velocity as 10.1±1.2 km s\(^{-1}\), however there is an issue with this as described further in appendix A.
nent (bulge, disk and halo) axisymmetric model (Model III from Bajkova & Bobylev 2017). In addition, the Galaxy gravitational potential is supplemented with the more realistic, non-axisymmetric and time dependent terms, which take into account the influence of the central bar and the spiral density wave (Palous et al. 1993; Fernández et al. 2008; Bajkova & Bobylev 2019).

In order to take account of the uncertainties in the astrometric parameters of the star and associations, each one was replaced by 1000 clones, each with astrometric parameters drawn from a multivariate normal distribution. This is done making use of the covariance matrix of astrometric parameters from Gaia DR2 (Gaia Collaboration et al. 2018) for the star and from the BANYAN Σ association models for the associations (Gagné et al. 2018a). Such a procedure is superior to the individual, independent random drawing of each parameter that ignores their mutual dependence.

From this process we have probability distribution functions of the separation distance between HD 95086 and the centre of the two associations. By comparing the cumulative distribution functions for the two associations we can determine which association HD 95086 was more likely closer to the centre of in the past. This is shown in Figure 2. From this we find that although HD 95086 is currently approximately equally close to the centre of both associations, tracing back in time to 10 Myr, we find that the likelihood of HD 95086 being closer to Carina was greater by a factor of between 2 and 4. This greatly strengthens our conclusion of HD 95086 being a likely Carina member as long as it is >10 Myr old. The ages of HD 95086 and Carina are assessed in the following two sections.

The main caveat here is that we have relied on the association models included as part of the BANYAN Σ algorithm. Recent research by Lee & Song (2019) implements a new algorithm for determining association models. They find that the parameters for most associations agree with those of Gagné et al. (2018a), but they do find significant differences for Carina. Their code is not public, but they do provide some details of the association models.

The model of Gagné et al. (2018a) locates the centre of the Carina association at $\mathbf{XYZ} = (7.2, -50.8, 18.0)$ pc and $\mathbf{UVW} = (-10.8, -21.9, -5.7)$ km s$^{-1}$, whereas the model of Lee & Song (2019) locates the centre of the Carina association at $\mathbf{XYZ} = (12.3, -114.7, -18.3)$ pc and $\mathbf{UVW} = (-10.6, -22.5, -4)$ km s$^{-1}$, i.e. there is a large shift in $Y$ but the other coordinates are not greatly changed. Their work does not include associations beyond 100 pc, such as LCC, and it is unclear how this might effect their results. Nonetheless, we can estimate how much using their model of Carina rather than that of Gagné et al. (2018a) would affect our results. We find that the distance from HD 95086 to the centre of Carina is not significantly changed by this, being 39 pc for the former model and 42 pc for the latter and so we do not expect it to impact our conclusions about the membership of HD 95086.

3 AGE ANALYSIS OF THE CARINA ASSOCIATION

The age of Carina has previously been estimated as 45$^{+11}_{-7}$ Myr (Bell et al. 2015) based on isochrones and >28 Myr based on kinematics (Miret-Roig et al. 2018). However, Schneider et al. (2019) find that Carina has an age closer to that of the $\beta$ Pic Moving Group based on Lithium measurements. We, therefore, consider it worthwhile to re-evaluate the age of Carina.

3.1 The age of Carina inferred from stellar evolution models

Figure 3 shows the colour magnitude diagram (CMD) for the stars that we have identified as potential members of the Carina association. For reference, we also plot the zero age main sequence (ZAMS) line, assuming [Fe/H]=0. We see that the majority of the stars lie close to ZAMS except for most of the M stars, which are above it. Offsets from the ZAMS line can be explained by a combination of the stars still being in the pre-main sequence phase, reddening due to the extinction and (in some cases) binarity...
The effect of extinction has been estimated for some of the stars in our sample, with an average of $A_G = 0.6$ and $E(BP-RP)= 0.3$ (shown by the red arrow in Figure 3). This is shown here for illustration and not corrected for as the extinction and reddening estimates provided by Gaia are not expected to be accurate for individual stars (Andrae et al. 2018) and the sample is too diverse (e.g. distances to our stars range from 30 to 100 pc) for the average to be an accurate estimate for individual stars.

HD 95086 has previously been identified as a giant star with Houk & Cowley (1975) giving it the classification A8III. However, as seen here and already noted by Rameau et al. (2013), its position on the CMD clearly places it close to the ZAMS line with a temperature and luminosity (see Table B1) that are consistent with those expected for an A8V star (e.g. Pecaut & Mamajek 2013; Eker et al. 2018). Similarly, m Car and iot Hyi are both listed as having a spectral classification of IV-V by Houk & Cowley (1975) and Gray et al. (2006) respectively, yet both are only slightly offset from ZAMS and their offsets can be explained by a combination of extinction and being in the pre-main sequence phase of their evolution, so they are expected to be too young to have evolved off the main sequence.

Here we take a renewed look at the age inferred from stellar evolution models using the Bayesian inference code of del Burgo & Allende Prieto (2018) and incorporating the latest data from Gaia DR2 (Gaia Collaboration et al. 2018). This Bayesian analysis makes use of the PARSEC v1.2S library of stellar evolution models (Bressan et al. 2012; Chen et al. 2014, 2015; Tang et al. 2014). It takes as input the absolute $G$ magnitude (obtained from the apparent magnitude and the parallax), $G_{BP}-G_{RP}$ colour, [Fe/H] and their uncertainties, returning theoretical predictions for other stellar parameters. We have assumed solar metallicity with [Fe/H]=0.00±0.20 and adopted the Gaia photometry passbands ($G$, $G_{BP}$, and $G_{RP}$) from Maíz Apellániz & Weiler (2018). As a prior, we assume that all of our stars are in the pre-main sequence phase due to the expected youth of the young association.

We determine ages for all of the stars in our membership list (Table 1). We then multiply the posterior likelihoods of the individual stars to determine the age of the association under the assumption that the members are coeval. We first consider only the most likely members (the 11 stars with a >99% probability of being in Carina) in order to have greater confidence that our age is not biased by stars that may not actually be members. We find that m Car, the only B star in the list, is just 3.3±0.4 Myr and so is excluded from this calculation as a clear outlier. Combining the posterior likelihoods for the other 10 stars in this group results in a posterior distribution that is shown in Figure 4. The mode and 68% uncertainties of this distribution are 13.3±1.4 Myr. This is much lower than pre-Gaia estimates due to the accuracy of the Gaia data used, both for the selection of Carina members and the age estimation. If we expand our sample for this calculation to include all stars with a membership probability >90% (19 objects in total) then we find an age of 14.7±0.8 Myr for the association, consistent with the age for just the most probable members, although we consider the age for just the most probable members to be the more reliable value.

As noted in subsection 2.1, Lee & Song (2019) derived a model for the Carina association that is different to the one used in this paper from Gagné et al. (2018a), primarily in terms of its Galactic $Y$ coordinate. If the model from Lee & Song (2019) is correct, then some of the stars that we have considered as Carina members in this paper may not be Carina members after all. However, we do not find any correlation between a star’s $Y$ coordinate and its age and so would not expect this to have a strong effect on the age of the Carina association derived in this section.

For the particular case of HD 95086, Meshkat et al. (2013)

Note that WISE J080822.18-644357.3 is not included here. (Murphy et al. 2018) show that the PARSEC isochrones do not give a good fit for this particular star. For a more detailed analysis of this star’s age we refer the interested reader to their paper.

Figure 3. $M_G$, the absolute magnitude in the $G$ band, versus $G_{BP}-G_{RP}$ colour for Carina members identified in this paper (shown with star symbols, where the colour signifies the membership probability). The dashed line shows the zero age main sequence for [Fe/H]=0. The red arrow shows the average extinction vector for the sample.

Figure 4. Posterior distribution for the age of the Carina association (red line) and HD 95086 (blue line).
used isochrone fitting to determine an age of 17±4 Myr. From our analysis, the likely age is found to be 15±4 Myr (where this age is the mean of the posterior probability distribution shown in Figure 4). Judging by the age, this would still be a good fit to LCC, for which the average age is 16-17 Myr (and the stars are known to have an age spread of around 10 Myr Mamajek et al. 2002; Preibisch & Mamajek 2008; Pecaut et al. 2012). This would not be a good fit to the previous age of Carina, but it does match well with our revised analysis. In other words, the similarity between our new age for Carina and the expected age for LCC, means that HD 95086 is consistent with membership of both associations based solely on its age.

As a by-product of this process, we also infer various other stellar properties such as effective temperature and mass. Whilst these properties are not relevant to the current study, we include them in appendix B as they may be of use to the community.

3.2 Kinematic age of Carina

In addition to updating the age inferred from stellar evolution models, we also re-assess the kinematic age so that we can compare both using the same data and association membership list. In order to re-evaluate the kinematic age of Carina, we have analysed how the distribution of mutual distances of the member stars changes with time. We do this using the method described in subsection 2.1, but this time tracing back the orbits of the individual member stars rather than the centre of the association to determine when they were closest together. As before, each star is cloned 1000 times with the parameters drawn from a multivariate normal distribution defined by the uncertainties on the observations.

The results of our trace back analysis are shown in Figure 5. The plot shows the mode and 68% highest probability density interval of the mutual distances between the star clones, using just the stars with a >90% membership likelihood (according to our BANYAN Σ analysis in section 2). We find that as we trace back the locations of the Carina members, the average distance between the members remains roughly constant for ~20 Myr before the orbits diverge, meaning that the association was born within the past 20 Myr and has exhibited little expansion since that time. We note that we also tested selecting just the members with a >99% likelihood. In this case the results are broadly consistent, albeit with an increased variation in the mode. This age is somewhat smaller than the 28 Myr minimum found by Miret-Roig et al. (2018), with the difference being primarily due to using a different list of members and the improvements in the Gaia data from DR1 to DR2.

Unfortunately, we are unable to precisely determine the age through this method due to the large uncertainties, as can be seen by the grey region in Figure 5. This is not unexpected. Riedel et al. (2017) simulated the expansion of an association and then used a similar method of cloning members and tracing them back to determine how accurately the age of an association can be determined through this method when assuming the accuracy of the final Gaia data release. They found that this method could only narrow down the age to within about 10 Myr of the real age. The main issue is the uncertainty on the RVs. This is typically around 1-10%, whilst the uncertainties on the other position and velocity parameters are around 0.01-0.1%.

For these reasons, we take the age inferred from the stellar evolution models as the more accurate estimate of the age. That said, our kinematic age estimate does still provide extra evidence for a younger age than the previous analyses.

4 DISCUSSION

4.1 The age of Carina

In section 3, we found that the age of Carina based on stellar evolution models is 13.3±1.1 Myr. We also found that, whilst we could not precisely determine the age from our kinematic analysis, the analysis does indicate an age younger than ~20 Myr. Our two approaches give results that are, therefore, in agreement. Whilst this young age is in conflict with the work of Bell et al. (2015) and Miret-Roig et al. (2018) (who proposed ages of 45±12 Myr and >28 Myr respectively), other recent research does also point towards a younger age for Carina. For instance, Schneider et al. (2019) found that the lithium measurements suggest an age similar to the β Pic Moving Group (23±3 Myr according to Mamajek & Bell 2014, and references therein). Ujjwal et al. (2020) used a similar approach to our stellar evolution model analysis, but defined association membership using LACEwING and determined ages using MIST isochrones. Their analysis resulted in a mean age of 16.6 Myr. These results give us confidence that the Carina association is younger than previously thought.

4.2 Planet masses

HD 95086b was first detected by Rameau et al. (2013) in L’ (3.8 μm) images from VLT/NaCo. Comparing the observed luminosity to ‘hot-start’ evolutionary models (Baraffe et al. 2003) they estimated the mass of the planet as being between
4 and 5 $M_J$ based on an age estimate of 10 and 17 Myr respectively. De Rosa et al. (2016) re-observed the planet in $H$ (1.5-1.8 $\mu$m) and $K_s$ (1.9-2.2 $\mu$m) wavebands with Gemini/GPI. They also compared their detections with the ‘hot-start’ models of Baraffe et al. (2003), finding masses of 2.7 and 4.4 $M_J$ for the $H$ and $K_s$ observations respectively, assuming and age of 17 Myr. In addition, they also considered ‘cold-start’ models from Mordasini (2013). Comparing to these they found masses of 3.1 and $> 9.1$ $M_J$ for the $H$ and $K_s$ observations, respectively. They did not consider younger ages but we can estimate from their Figure 10 that their $H$-band photometry is consistent with a mass as low as $\sim 1.5$ $M_J$ if an age of 10 Myr is considered.

The implications of a lower mass are important when considering the interaction between the planet and the debris disc. Su et al. (2017) demonstrated that a planet of 4.4 $M_J$ would require an eccentricity of $\approx 0.29$ if it is responsible for the inner edge of the debris disc as detected by ALMA. Alternatively a lower mass planet could exist beyond the orbit of the known planet and be responsible for clearing debris from that region of the system. In this paper we propose that this system is a member of the Carina association. The previous estimates of the age of Carina would support a more massive planet and the need for a high eccentricity or extra planet in the system could be circumvented. However, our updated age of Carina of $13.3^{+1.1}_{-0.6}$ Myr implies a lighter mass for the planet, which reinforces the need for another planet in the system in order to explain the location of the disc’s inner edge.

HD 95086 is not the only star in Carina known to host a low mass companion. A companion to HD 44627 (also known as AB Pic) was discovered by Chauvin et al. (2005). The association membership of HD 44627 was originally identified as Tuc-Hor (Song et al. 2003). Torres et al. (2008) reclassified it as a member of Carina, as is supported by our results from BANYAN $\Sigma$. Lee & Song (2019), however, find it to be a member of Columba. Prior to this paper, the ages of Tuc-Hor, Carina and Columba were all estimated to be $\sim 30$ Myr. Based on this age, both Chauvin et al. (2005) and Bonneau et al. (2010) inferred a mass of $\sim 13$ $M_J$ for the companion, leaving it unclear whether this companion is a planet or brown dwarf. A younger age, as proposed by our analysis, would reduce the mass required to explain the observations and clarify that this companion is most likely a gas giant rather than a brown dwarf.

4.3 Gas in the HD 95086 debris disc

Unlike protoplanetary discs, debris discs are gas poor. Nonetheless, in recent years detections of CO gas have been made in a number of debris disc systems (see Hughes et al. 2018, for a recent review). Kral et al. (2017) developed a model of CO gas released in the collisional cascade to explain the levels of gas seen in these systems. They made predictions for which discs are most likely to be good targets for detecting gas and found the HD 95086 disc to be one of the best candidates. Booth et al. (2019) searched this system for CO gas and found tentative evidence of its existence at an RV of $8.5^{+0.2}_{-0.1}$ km s$^{-1}$. They demonstrated that, given the large number of channels in the data and assuming Gaussian noise, four channels would be expected to have a CO line flux equivalent to that measured. Nonetheless, the consistency between the radial profile of the gas and dust; the measured gas mass and predicted gas mass; and the measured RV and the stellar RV found by Madsen et al. (2002), all gave weight to this being a real signal. In subsection 2.1, we demonstrated that even if it is a member of LCC, the latest data predict that the RV should then be closer to 16.4 km s$^{-1}$ and in the more likely case that it is a member of Carina, the RV should be close to $17.1^{+0.6}_{-0.3}$ km s$^{-1}$, in perfect agreement with the spectroscopic measurement of $17.2^{+0.2}_{-0.2}$ km s$^{-1}$ (Módr et al. 2013b). From this we can conclude that the tentative detection of gas from Booth et al. (2019) must, in fact, just be a spurious noise signal and no gas has yet been detected in the HD 95086 debris disc.

4.4 Carina in the context of nearby young associations

Elmegreen (1993) proposed a three part scenario of recent star formation close to the Sun. In this scenario, local star-forming activity began around 60 Myr ago when the Carina arm passed through the local gas. One of the associations that formed in this process resulted in the creation of the Lindblad ring, the fragmentation of which then created the nearest giant molecular clouds Orion, Sco-Cen and Perseus around 20 Myr ago. More recently a third generation formed in the region of Ophiuchus and Taurus. Miret-Roig et al. (2018) suggested that Tucana-Horologium, Columba and Carina likely formed as the first generation in this scenario, whilst our results show that it would have formed as part of the second generation along with the $\beta$ Pictoris moving group. Naturally, it is likely that the ages of many of the other young local associations will also be revised with new data and further analysis. For instance, Goldman et al. (2018) recently identified a moving group within LCC and identified four sub-groups with ages between 7-10 Myr, much younger than the 17 Myr age previously determined for LCC by Pecaut & Mamajek (2016).

4.5 Cluster expansion

In section 2.1 we considered the distance of HD 95086 from the centre of the Carina and LCC associations. This implicitly assumes that the stars in these associations formed in a gravitationally-bound cluster and this cluster is now expanding from a central point. Observations of present star formation show that stars form in a wide variety of environments from gravitationally-bound clusters to hierarchical structures and even in isolation (e.g. Allen et al. 2007). Whilst some OB associations do show clear signs of expansion from a central point (Melnik & Dambis 2020), Ward et al. (2020) demonstrate that for many associations the stellar motions are not consistent with expansion from a central point, preferring hierarchical formation models and localised expansion. This means that we must be cautious in interpreting HD 95086’s closer distance to the centre of Carina than LCC in the past as proof that is definitely a Carina member. Ideally this would be verified by tracing back the individual orbits of LCC members, but the large number of LCC members makes this computationally expensive and beyond the scope of this work. Nonetheless, the degree of difference between the distances to the cluster centres does give us confidence in the results of this simplified method.
5 CONCLUSIONS

In this paper we have analysed the age of the Carina nearby young association in light of the latest data. We began by checking the likelihood of previously proposed Carina candidates. We then applied a Bayesian stellar evolution analysis to these stars and found a mean age for the most likely candidates (membership probability $>$99%) of $13.3_{-0.6}^{+1.1}$ Myr. We also attempted to determine the age from a kinematic perspective by tracing back the stellar orbits. This analysis suggested that the age is likely $<$20 Myr, however, the uncertainties are too large to make any firm conclusions from the kinematics.

In the process of this work we also proposed that HD 95086 – a star that hosts both a directly imaged planet and a resolved debris disc – is a likely Carina member for the first time with a probability of 71%.

Whilst we argue that HD 95086 is a member of Carina rather than LCC, the age we infer for the star is consistent with previous estimates and so the inferred mass of HD 95086b remains the same. Our reassessment of the radial velocity of the star does allow us to rule out the tentative detection of CO gas in the debris disc reported by Booth et al. (2019) as the radial velocity of the reported gas line is inconsistent with that of the star.

Our finding that Carina is much younger than most previous estimates prompts a reanalysis of the local star formation history, showing that Carina may be of a similar age to LCC.

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This research has made use of the SIMBAD database (Wenger et al. 2000), operated at CDS, Strasbourg, France. This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. This work has made use of Topcat (Taylor 2005).

DATA AVAILABILITY

The data underlying this article are available either in the article or from the Gaia Archive at https://gea.esac.esa.int/archive/ using the identifiers listed in Table 1. Data resulting from this work will be made available upon reasonable request.
APPENDIX A: RADIAL VELOCITIES FROM KHARCHenko ET AL. (2007)

In the process of this work we noticed that there is an issue with the catalogue of Kharchenko et al. (2007). Kharchenko et al. (2007) compiled RVs from a number of other sources in the literature including Gontcharov (2006). However, the source of many of the stars is incorrect. There are 396 stars in Kharchenko et al. (2007) that are listed as coming from the catalogue of Gontcharov (2006) but do not actually appear in that catalogue. They likely came from other literature sources. Most intriguingly, 350 of them have RVs that match those in Madsen et al. (2002). Unlike Gontcharov (2006), Madsen et al. (2002) did not determine RVs by observing stars spectroscopically. Instead, they made use of membership lists of young associations and determined, based on the Hipparcos parallaxes and proper motions, what RVs stars should have if they are in the given young associations. Confusing RVs measured in this way with those measured by spectroscopy is problematic as firstly the assumption of membership in a young association may not be correct and, secondly, even if it is, the true RV of a star may be somewhat different from that expected due to interactions with other stars. This has previously be noted by Murphy et al. (2015), although they did not specifically note that HD 95086 is one of the stars affected.

APPENDIX B: STELLAR DATA

In addition to the ages, the code of del Burgo & Allende Prieto (2018) also infers various other properties of the stars. Whilst not relevant to current study, we include these in Table B1 as they may be useful to the community for other purposes.

This paper has been typeset from a TeX/LaTeX file prepared by the author.
| Name                      | $\log L$ | $T_{\text{eff}}$, K | $M_*$, $M_\odot$ | $R_*$, $R_\odot$ |
|---------------------------|----------|---------------------|-------------------|------------------|
| HD 49855                  | -0.224 ± 0.006 | 5430 ± 30 | 0.95 ± 0.05 | 0.873 ± 0.015 |
| UCAC3 53-40215            | -0.854 ± 0.005 | 3799 ± 21 | 0.69 ± 0.03 | 0.864 ± 0.012 |
| 2MASS J08040534-6316396   | -1.015 ± 0.006 | 3470 ± 50 | 0.58 ± 0.09 | 0.860 ± 0.022 |
| 2MASS J09315840-6209258   | -1.008 ± 0.013 | 3260 ± 50 | 0.45 ± 0.09 | 0.985 ± 0.018 |
| HD 42270                  | -0.131 ± 0.008 | 5280 ± 70 | 1.003 ± 0.014 | 1.03 ± 0.03 |
| 2MASS J08063608-7444249   | -1.140 ± 0.004 | 3500 ± 30 | 0.57 ± 0.05 | 0.732 ± 0.013 |
| HD 37402                  | 0.246 ± 0.010 | 6231 ± 11 | 1.21 ± 0.04 | 1.139 ± 0.013 |
| HD 298936                 | -0.384 ± 0.009 | 4660 ± 50 | 0.923 ± 0.029 | 0.99 ± 0.03 |
| m Car                     | 1.877 ± 0.017 | 10470 ± 120 | 2.84 ± 0.22 | 2.64 ± 0.04 |
| 2MASS J06262199-7516404   | -1.081 ± 0.004 | 3690 ± 50 | 0.61 ± 0.03 | 0.705 ± 0.018 |
| V* V479 Car               | 0.020 ± 0.007 | 5130 ± 50 | 1.151 ± 0.016 | 1.24 ± 0.03 |
| HD 44627                  | -0.227 ± 0.006 | 5020 ± 40 | 0.974 ± 0.014 | 1.020 ± 0.023 |
| HD 55279                  | -0.372 ± 0.006 | 4800 ± 40 | 0.903 ± 0.013 | 0.942 ± 0.022 |
| AL 442                    | -1.121 ± 0.024 | 3140 ± 30 | 0.36 ± 0.07 | 0.933 ± 0.023 |
| 2MASS J07441105-6458052   | -1.094 ± 0.005 | 3915 ± 22 | 0.636 ± 0.016 | 0.617 ± 0.006 |
| 2MASS J09180165-5452332   | -1.23 ± 0.04 | 2938 ± 13 | 0.23 ± 0.06 | 0.94 ± 0.04 |
| 2MASS J07065772-5353463   | -0.836 ± 0.004 | 3816 ± 27 | 0.68 ± 0.04 | 0.874 ± 0.014 |
| WISE J080822.18-644357.3 | -2.151 ± 0.011 | 3172 ± 16 | 0.244 ± 0.019 | 0.278 ± 0.006 |
| 2MASS J07013884-6236059   | -0.987 ± 0.007 | 3720 ± 50 | 0.63 ± 0.04 | 0.774 ± 0.020 |
| TYC 8602-718-1            | -0.436 ± 0.008 | 4950 ± 40 | 0.854 ± 0.026 | 0.824 ± 0.021 |
| HD 83096                  | 0.686 ± 0.007 | 6760 ± 60 | 1.53 ± 0.09 | 1.61 ± 0.03 |
| iot Hyi                   | 0.630 ± 0.010 | 6520 ± 40 | 1.43 ± 0.13 | 1.62 ± 0.04 |
| 2MASS J04082685-7844471   | -0.964 ± 0.004 | 3880 ± 50 | 0.658 ± 0.020 | 0.729 ± 0.019 |
| 2MASS J08194309-7401232   | -1.218 ± 0.017 | 3081 ± 26 | 0.33 ± 0.06 | 0.864 ± 0.009 |
| HD 95086                  | 0.829 ± 0.003 | 7573 ± 9 | 1.587 ± 0.024 | 1.508 ± 0.007 |
| TYC 9200-446-1            | -0.141 ± 0.006 | 5570 ± 40 | 0.97 ± 0.04 | 0.913 ± 0.017 |

Table B1. Stellar properties (luminosity, effective temperature, mass and radius) inferred by the code used in subsection 3.1.