A Young Ultramassive White Dwarf in the AB Doradus Moving Group

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Abstract

We use Gaia Data Release 2 (DR2) kinematic data and white dwarf evolutionary models to determine that the young and ultramassive 1.28 ± 0.08 $M_\odot$ white dwarf GD 50 is a likely member of the AB Doradus moving group (ABDMG). Comparison with the Montréal white dwarf evolutionary models and the MESA Isochrones and Stellar Tracks (MIST) main-sequence lifetimes imply a total age of 117 ± 26 (±13 statistic, ±22 systematic) Myr, accounting for all possible C/O/Ne core compositions and using the Pleiad white dwarf LB 1497 as a comparison benchmark. This is the first white dwarf cosmochronology age for a nearby young moving group, and allows us to refine the age of the ABDMG at 133^{+15}_{-20} Myr by combining it with its independent isochronal age. GD 50 is the first white dwarf member of the ABDMG and is located at only 31 pc from the Sun, making it an important benchmark to better understand the star formation history of the Solar neighborhood.

Key words: open clusters and associations: individual (AB Doradus moving group, Pleiades) – stars: individual (GD 50) – stars: kinematics and dynamics – white dwarfs

1. Introduction

The recent publication of more than a billion precise trigonometric parallaxes and proper motions in the Gaia Data Release 2 (DR2; Gaia Collaboration et al. 2018b; Lindegren et al. 2018) is instigating a revolution in several branches of astrophysics, which includes our understanding of Galactic kinematics and the star formation history of the Solar neighborhood. This large influx of high-quality kinematic data is enabling the discovery of thousands of new low-mass members in known young associations (e.g., Gagné & Faherty 2018) where the initial mass function is predicted to peak (e.g., Chabrier 2005; Bochanski et al. 2011), as well as brand new young associations of stars that were not recognized before (e.g., Oh et al. 2017; Faherty et al. 2018 and Gagné Faherty & Mamajek 2018).

Another branch of astrophysics that is strongly affected by Gaia DR2 is the study of white dwarfs. These objects are too faint (absolute G-band magnitudes of 10–15; Gaia Collaboration et al. 2018a) to have been efficiently surveyed by large trigonometric distance missions such as Hipparcos (Perryman et al. 1997), but Gaia DR2 can now detect them efficiently at distances well above 100 pc (Gaia Collaboration et al. 2018a). This revolution of stellar astrophysics in the Solar neighborhood opens the door to a vastly improved efficiency in the search and characterization of nearby white dwarfs at well-calibrated ages through young associations within 150 pc of the Sun.

In this Letter, we independently recover the ultramassive DA white dwarf GD 50 as a strong candidate member of the AB Doradus moving group (ABDMG; Zuckerman et al. 2004; Zuckerman & Song 2004) with recent age estimates that range from ∼100–125 Myr (Luhman et al. 2005; Barenfeld et al. 2013) to 130–200 Myr (Bell et al. 2015). Dobbie et al. 2006 used the model-predicted distance for GD 50 to estimate its UVW space velocity and found that it is similar to the Pleiades.

The authors note that GD 50 may therefore have formed with the Pleiades, or with the “local association” that is now thought to be a non-coeval stream (Mamajek 2016) that includes the Pleiades, the ABDMG, and other unrelated stars. However, they find no clear explanation for the discrepant distance of GD 50 (∼31 pc versus ∼135 pc for the Pleiades) and they suggest that it might have been ejected early after its formation. The lack of precise kinematic measurements and methodologies to distinguish stars from different young associations in this large range of distances prevented a clear conclusion on the membership of GD 50. As a consequence of this ambiguity, GD 50 was missing in all compilations of candidate members of the Pleiades association and the ABDMG (e.g., Torres et al. 2008; Malo et al. 2013; Sarro et al. 2014; Riedel et al. 2017; Gagné et al. 2018c). GD 50 was also targeted in a direct-imaging search for planetary-mass companions due to its youth and proximity, but giant planets with masses above $4 M_{Jup}$ at separations larger than 6.2 au were excluded at a 5σ significance Xu et al. (2015).

We use updated GD 50 kinematics from Gaia DR2 and the BANYAN $\Sigma$ Bayesian classification algorithm (Gagné et al. 2018c) to demonstrate that GD 50 is a likely member of the ABDMG (Section 2), and has a negligible Pleiades membership probability. We show that the discovery of a single white dwarf member in the ABDMG is consistent with a log-normal initial mass function anchored on its AFG-type members (Section 3). This determination is strengthened by an investigation of the total age of GD 50, which also provides us with the first white-dwarf-based age determination for a young moving group of the Solar neighborhood (Section 4). A conclusion is presented in Section 5.

2. Membership

GD 50 was recovered as a high-likelihood candidate member of the ABDMG in a search for members of young associations with the 100 pc Gaia DR2 sample (Gagné & Faherty 2018), although this study originally excluded white...
dwarf candidates. This search uses the BANYAN $\Sigma$ Bayesian membership classification algorithm (Gagné et al. 2018c) to determine the probability that a given star is a member in one of the nearest 27 young associations or in the field, defined as all associations younger than 1 Gyr within 150 pc of the Sun.

In summary, each young association is modeled with a multivariate Gaussian density in six-dimensional Galactic position and space velocity $XYZUVW$, and the Galactic field within 300 pc is modeled with a mixture of 10 multivariate Gaussians. BANYAN $\Sigma$ uses Bayes' theorem to compare observables with the multivariate Gaussian models, and marginalizes over radial velocity or distance—with analytical solutions to the marginalization integrals—when these measurements are not available. The 27 associations considered in BANYAN $\Sigma$ include the ABDMG and the Pleiades association, among others.

The Gaia DR2 proper motion and parallax of GD 50 are reported in Table 1. Analyzing these kinematics with the BANYAN $\Sigma$ Bayesian membership classification algorithm yields a 99.7% membership in the ABDMG, and a negligible Pleiades membership probability. BANYAN $\Sigma$ predicts an optimal radial velocity of $17.5 \pm 1.4$ km s$^{-1}$, assuming membership in the ABDMG. The resulting UVW space velocity of GD 50 is listed in Table 1, and compared with the known members of the ABDMG in Figure 1.

Measuring the radial velocity of GD 50 with a precision of a few km s$^{-1}$ would be required to fully confirm its kinematic match to the ABDMG; however, this is challenging because of the strong gravitational redshift at the surface of GD 50. Dobbie et al. 2006 measured a radial velocity of $176 \pm 4.3$ km s$^{-1}$ from the line core positions of H$\alpha$ and H$\beta$, but the correction due to gravitational redshift ($162 \pm 11$ km s$^{-1}$, calculated from fundamental properties given in Table 1) makes the resulting heliocentric radial velocity ($14 \pm 12$ km s$^{-1}$) highly imprecise, albeit consistent with the prediction of BANYAN $\Sigma$.

In Figure 2, we show the Gagné et al. (2018c) compilation of bona fide members of the ABDMG in a Gaia DR2 absolute $G$ versus $G - G_{RP}$ color–magnitude diagram compared with the nearest 100 pc Gaia DR2, the empirically corrected 110–200 Myr MESA Isochrones and Stellar Tracks (MIST) tracks, as well as the total white dwarf ages. The total white dwarf ages are based on MIST for the pre-white dwarf phases and the Montréal C/O core cooling tracks$^7$ (see also Holberg & Bergeron 2006; Kowalski & Saumon 2006; Bergeron et al. 2011; Tremblay et al. 2011). GD 50 falls at a position consistent with the white dwarf isochrone tracks at the total age of the ABDMG, and forms an extension of its sequence across the stages of stellar evolution.

### 3. The Initial Mass Function of the ABDMG

In this section we determine whether the discovery of a white dwarf member in the ABDMG is consistent with its present-day mass function. We determined the masses of bona fide members compiled by (Gagné et al. 2018c) with the fiducial solar-metallicity MIST isochrones (Choi et al. 2016) with

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**Table 1**

Properties of GD 50

| Property | Value | Reference |
|----------|-------|-----------|
| $V_{\text{hel}}$ (km s$^{-1}$) | $17.5 \pm 1.4$ | 1 |
| $V_{\text{max}}$ (km s$^{-1}$) | $14 \pm 12$ | 3 |
| X (pc) | $-23.59 \pm 0.04$ | 2 |
| Y (pc) | $-3.717 \pm 0.007$ | 2 |
| Z (pc) | $-20.10 \pm 0.04$ | 2 |
| $U^*$ (km s$^{-1}$) | $-7 \pm 1$ | 2 |
| $V^*$ (km s$^{-1}$) | $-28.3 \pm 0.2$ | 2 |
| $W^*$ (km s$^{-1}$) | $-14.2 \pm 0.9$ | 2 |
| Photometric Properties | | |
| $B$ (Johnson) | $14.063 \pm 0.0032$ | 4 |
| $B - V$ (Johnson) | $-0.276 \pm 0.0036$ | 4 |
| $G_{\text{BP}}$ (Gaia DR2) | $13.782 \pm 0.007$ | 1 |
| $G$ (Gaia DR2) | $14.0354 \pm 0.0005$ | 1 |
| $G_{\text{RP}}$ (Gaia DR2) | $14.336 \pm 0.001$ | 1 |
| $M_{\text{AB}}$ (SDSS DR12) | $13.396 \pm 0.003$ | 5 |
| $R_{\text{AB}}$ (SDSS DR12) | $13.760 \pm 0.003$ | 5 |
| $J_{\text{AB}}$ (SDSS DR12) | $14.282 \pm 0.004$ | 5 |
| $J_{\text{AB}}$ (SDSS DR12) | $14.640 \pm 0.004$ | 5 |
| $R_{\text{AB}}$ (Pan-STARRS DR1) | $13.831 \pm 0.004$ | 6 |
| $J_{\text{AB}}$ (Pan-STARRS DR1) | $14.290 \pm 0.002$ | 6 |
| $R_{\text{AB}}$ (Pan-STARRS DR1) | $14.678 \pm 0.003$ | 6 |
| $J_{\text{AB}}$ (Pan-STARRS DR1) | $14.972 \pm 0.005$ | 5 |
| $R_{\text{AB}}$ (Pan-STARRS DR1) | $15.168 \pm 0.004$ | 6 |
| $J_{\text{AB}}$ (Pan-STARRS DR1) | $14.75 \pm 0.03$ | 7 |
| $R_{\text{AB}}$ (Pan-STARRS DR1) | $14.86 \pm 0.04$ | 7 |
| $K_{\text{s}}$ (2MASS) | $15.120 \pm 0.138$ | 7 |
| $J$ (UKIDSS DR9) | $14.794 \pm 0.004$ | 8 |
| $H$ (UKIDSS DR9) | $14.890 \pm 0.007$ | 8 |
| $K$ (UKIDSS DR9) | $15.05 \pm 0.01$ | 8 |
| W1 (AIWISE) | $15.11 \pm 0.04$ | 9 |
| W2 (AIWISE) | $15.20 \pm 0.09$ | 9 |

**Fundamental Properties**

| Spectral type | DA1.2 | 10 |
| $T_{\text{eff}}$ (K) | $42700 \pm 800$ | 10 |
| $\log g$ | $9.20 \pm 0.07$ | 10 |
| Mass (M$_\odot$) | $1.28 \pm 0.02$ | 2 |
| Age (Myr) | $117 \pm 26$ ($\pm 13$ statistic, $\pm 22$ systematic) | 2 |

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**Notes.**

1. J2000 position at epoch 2015 from the Gaia DR2 catalog.
2. J2000 position at epoch 2000 calculated from the Gaia DR2 astrometric solution.
3. Optimal radial velocity predicted by BANYAN $\Sigma$ that assumes the most likely membership hypothesis (ABDMG).
4. UVW values presented here assume the optimal radial velocity produced by BANYAN $\Sigma$ that maximizes the ABDMG membership probability.

**References.** (1) Lindegren et al. 2018, (2) this work, (3) Dobbie et al. 2006, (4) Landolt 2009, (5) Alami et al. 2015, (6) Chambers et al. 2016, (7) Skrutskie et al. 2006, (8) Lawrence et al. 2007, (9) Kirkpatrick et al. 2014, (10) Gianninas et al. 2011.
stellar rotation ($v = 0.4 v_{\text{crit}}$) at 150 Myr, consistent with the age and metallicity of the ABDMG (Barenfeld et al. 2013; Bell et al. 2015). The individual masses were determined by selecting the nearest point on the MIST isochrone in $N\sigma$ separation. The $N\sigma$ distance is given by the absolute magnitude and color separations between the star and isochrone divided by the measurement errors on the position of the star in the color–magnitude diagram. We compiled these measured masses in logarithm space with a relatively large 0.4 dex bin size to obtain a preliminary present-day mass function for the members of the ABDMG bright enough to have a parallax in Gaia DR2. The bin size was selected to minimize the effects of small number statistics and systematics in the model-dependent mass determinations.

The white dwarf mass of GD 50 was determined with the Montréal white dwarf cooling tracks and the updated $T_{\text{eff}}$ and $\log g$ reported by Gianninas et al. 2011 for GD 50 (listed in Table 1 with its other fundamental parameters). Models at various C/O/Ne core compositions that span 50%/50%/0%, 0%/100%/0%, and 0%/0%/100%, were compared with the spectroscopic properties in a $10^4$-elements Monte Carlo simulation to account for measurement errors and the unknown core composition. We consider neon cores in addition to C/O cores because stellar evolution theory predicts that white dwarfs as massive as GD 50 are the progenitors of $>7 M_\odot$ stars, which burn oxygen in their later stages of life, and are expected to produce white dwarfs with O/Ne core compositions (Jones et al. 2013; Woosley & Heger 2015). We recovered a mass of $1.28 \pm 0.02 M_\odot$ with C/O core compositions, and a slightly lower mass of $1.27 \pm 0.02 M_\odot$ for a pure Ne core. Marginalizing over all possible core compositions with a uniform prior yields a mass of $1.28 \pm 0.02 M_\odot$, which we adopt here. We used thick hydrogen atmosphere models ($10^{-4}$ mass fraction), but we found that using thin hydrogen atmospheres ($10^{-10}$ mass fraction) had no effect on the estimated mass.

The progenitor mass of GD 50 was determined from the white dwarf mass and the initial-to-final mass relations of Kalirai (2013). Measurement errors on the initial-to-final mass relation coefficients and the final mass were assumed to follow a Gaussian distribution and were propagated with a $10^4$ Monte Carlo analysis, resulting in a progenitor mass of $7.8 \pm 0.6 M_\odot$ for GD 50. This mass corresponds to a main-sequence effective temperature of $\sim 22,000$ K (Choi et al. 2016), and to a main-sequence spectral type of $\sim B2$ (Pecaut & Mamajek 2013). The GD 50 progenitor mass was added to our ABDMG present-day mass function to obtain its initial mass function, displayed in Figure 3.

A fiducial log-normal initial mass function (with a central mass $m_c = 0.1 M_\odot$ and spread $\sigma = 0.7$ dex; Bochanski et al. 2011) was adjusted to match the $0.6-4 M_\odot$ members (corresponding to the AFG spectral classes), and is also displayed in Figure 3. This log-normal initial mass function is consistent with a $1.7^{+0.9}_{-0.5}$ white dwarf members in the ABDMG, which is indicative that we could have expected to discover a single white dwarf member at a 93% probability, and that there is only a $\sim 50%$ probability that at least one additional white dwarf member remains to be discovered in the region of $XYZ$ Galactic positions where the current ABDMG census of members is concentrated.

4. The Age of GD 50

GD 50 provides a unique opportunity to use a white dwarf as a cosmochronometer to determine the age of a nearby young
In this section, we use the Montréal white dwarf cooling tracks with the MIST isochrones to determine the total age of GD 50, accounting for all of its stages of stellar evolution.

We used the $T_{\text{eff}}$ and log $g$ values of GD 50 listed in Table 1 to determine its cooling age. Simon et al. (2015) and Simon (2018) demonstrated that various assumptions on the C/O core compositions can have a non-negligible effect on the cooling age of a white dwarf, depending on its mass and age. This effect could also be expected for different Ne compositions. We therefore used the Montréal white dwarf cooling tracks with thick hydrogen atmospheres ($10^{-4}$ mass fraction) and various C/O/Ne core compositions that span 100% carbon, 100% oxygen, and 100% neon to determine the cooling age of GD 50. We used a $10^4$-elements Monte Carlo simulation to propagate the measurement errors of $T_{\text{eff}}$ and log $g$. We found cooling ages of $81 \pm 13$ Myr, $74 \pm 12$ Myr, $69^{+17}_{-11}$ Myr, and $65^{+20}_{-12}$ Myr for respective core compositions of 50%/50% C/O, pure O, 50%/50% O/Ne, and pure Ne. We repeated this age determination with thin hydrogen atmospheres ($10^{-10}$ mass fraction), and found that it had only a small effect, with cooling ages $\sim 5$ Myr larger than the thick hydrogen atmospheres.

For each Monte Carlo realization, a progenitor mass was calculated using the Kalirai (2013) relation, and the MIST isochrones were used to determine the total time between the birth and white dwarf phase from the mass of each synthetic object. The uncertainties on the parameters of the Kalirai (2013) relation were included in the Monte Carlo analysis, and yielded typical MIST isochrone lifetimes of $44 \pm 7$ Myr when marginalizing over all possible core compositions. These lifetimes were combined to the cooling ages to determine a total age of $117 \pm 13$ Myr for GD 50—the core compositions that include heavier elements tend to have slightly smaller masses, and slightly longer stellar lifetimes, which counter-balances part of the uncertainty in total age caused by the cooling age–core composition correlation. Our age estimate is on the young side of recent age estimates for the ABDMG (e.g., $149^{+31}_{-19}$; Bell et al. 2015), and consistent with the age of the Pleiades ($112 \pm 5$ Myr; Dahm 2015). This is the first age determination of a nearby young moving group based on white dwarf evolution theory.

In principle, it would be possible to constrain the core composition of GD 50 by adopting an ABDMG age from an independent method (e.g., see Bell et al. 2015), or by comparing the spectroscopic distance of different core compositions with the Gaia DR2 parallax measurement (using white dwarf mass–radius relations, e.g., see Bécard et al. 2017).
We attempted to do so, but found no useful constraints on the core composition of GD 50. For the first method this is due to the large measurement errors on the isochronal age of the ABDMG, and for the second method it is due to the error bars on $T_{\text{eff}}$ and $\log g$ and the weak mass dependence on white dwarfs of C/O/Ne cores at young ages.

A comparison between GD 50 and the Pleiades white dwarf LB 1497 (Luyten & Herbig 1960) is warranted given their membership in coeval associations. LB 1497 has a lower mass of $1.05 \pm 0.03 M_\odot$, with correspondingly lower effective temperature ($32,700 \pm 500$ K) and surface gravity ($8.67 \pm 0.05$ dex; Gianninas et al. 2011). Using the same models and method as described above, we estimate a progenitor mass of $5.7 \pm 0.5 M_\odot$ for LB 1497, and a total age of $139^{+15}_{-15}$ Myr. This total age is the sum of the pre-white dwarf lifetime ($88^{+21}_{-16}$ Myr) and the cooling age ($50^{+9}_{-8}$ Myr). This total age is slightly older than the age of the Pleiades based on its updated lithium depletion boundary ($112 \pm 5$ Myr; Dahm 2015), which we suspect may be attributed to systematic uncertainties in the pre-white dwarf phase lifetimes that we estimated based on the MIST isochrones. We therefore assign a systematic uncertainty of $\pm 22$ Myr to our method, to bring the disagreement between the Pleiades age and the age of LB 1497 from $1.7\sigma$ to $1.0\sigma$. As a consequence of this estimated systematic uncertainty, we update the age of GD 50 to $117 \pm 26$ ($\pm 13$ statistic, $\pm 22$ systematic) Myr.

Because our age measurement is based on a method independent of the Bell et al. (2015) method, we can combine the two ages statistically to obtain a more precise age estimate for the ABDMG. To do so, we approximated the Bell et al. (2015) measurement with an asymmetrical Gaussian probability density function and multiplied it with our age probability density function. The resulting combined age for the ABDMG is $133^{+15}_{-20}$ Myr.

5. Conclusion

We present evidence that the ultramassive white dwarf GD 50 is a member of the ABDMG based on its updated Gaia DR2 kinematics and the BANYAN $\Sigma$ bayesian classification algorithm. We estimate a mass of $7.8 \pm 0.6 M_\odot$ for the progenitor of GD 50, and find that a log-normal initial mass function anchored on the AFG-type members of the ABDMG is consistent with at least one white dwarf member at a 93% statistical confidence. The inclusion of GD 50 in the list of ABDMG members makes it possible to use white dwarf cooling ages as a new method to constrain the age of ABDMG, independent of the lithium depletion boundary and isochrone methods. We use this method to find an age of $117 \pm 26$ Myr, which is on the younger side of recent age determinations based on isochrones. Neither the Gaia DR2 parallax nor literature ages for the ABDMG can constrain the relative compositions of C/O/Ne in the core of GD 50.

Our analysis corroborates the conclusion of Dobbie et al. (2006) that a single massive progenitor can form white dwarfs as massive as GD 50 without the need of invoking white dwarf mergers, which simulations have difficulty producing at a high enough rate to explain the number of observed ultramassive white dwarfs (Segretain et al. 1997). Identifying additional white dwarfs in young associations of the Solar neighborhood will provide powerful constraints on their ages, which are independent of other widely used methods.

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Software: BANYAN $\Sigma$ (Gagné et al. 2018c).

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