The Progenitor of the Vela Pulsar

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ABSTRACT

With Gaia parallaxes it is possible to study the stellar populations associated with individual Galactic supernova remnants (SNR) to estimate the mass of the exploding star. Here we analyze the luminous stars near the Vela pulsar and SNR to find that its progenitor was probably (≥90\%) low mass (8.1-10.3\(M_\odot\)). The presence of the O star \(\gamma^2\) Vel a little over 100 pc from Vela is the primary ambiguity, as including it in the analysis volume significantly increases the probability (to 5\%) of higher mass (>20\(M_\odot\)) progenitors. However, to be a high mass star associated with \(\gamma^2\) Vel’s star cluster at birth, the progenitor would have to run away star from an unbound binary with an unusually high velocity. The primary impediment to analyzing large numbers of Galactic SNRs in this manner is the lack of accurate distances. This can likely be solved by searching for absorption lines from the SNR in stars as a function of distance, a method which yielded a distance to Vela in agreement with the direct pulsar parallax. If Vela was a 10\(M_\odot\) supernova in an external galaxy, the 50 pc search region used in extragalactic studies would contain only \(\sim\) 10\% of the stars formed in a 50 pc region around the progenitor at birth and \(\sim\) 90\% of the stars in the search region would have been born elsewhere.

Key words: stars: massive – supernovae: general – supernovae

1 INTRODUCTION

We would like to understand which massive stars explode as supernovae and the nature of the resulting compact objects. Modern theoretical models (e.g., O’Connor & Ott 2011, Pejcha & Thompson 2012, Ertl et al. 2016, Sukhbold et al. 2016, Ghosh et al. 2021) find a complex mapping between progenitor mass and explosion driven by changes in core structure related to the balance between radiative and convective carbon burning (Sukhbold et al. 2018, Sukhbold & Adams 2020). In these modern models, essentially all stars either explode and produce neutron stars or fail to explode and produce black holes – “fall back” supernovae where the star explodes but a significant amount of mass falls back onto the proto-neutron star to form a black hole are extremely rare. In the absence of fall back, lower mass (<10\(M_\odot\)) black holes are produced either from explosions of stars stripped by pre-supernova mass loss/transfer or by the failed explosions of the more massive red supergiants. These produce black holes with the mass of the helium core (Kochanek 2014) because the Nadezhin (1980) mechanism (also see, e.g., Lovegrove & Woosley 2014, Fernández et al. 2018) ejects the weakly bound hydrogen envelope of the supergiant. None of these surveys of outcomes are based on full \textit{ab initio} core collapse simulations but instead use “calibrated” explosion models to explore outcomes. The outcomes in true core collapse simulations remain an open problem because of the complexity of the physics and the need for high resolution three-dimensional simulations (e.g., Bollig et al. 2021, Burrows et al. 2020, Pan et al. 2021).

To test these theoretical predictions, we need to observationally determine the mapping between progenitors and outcomes. The cleanest approach for the stars which explode is simply to measure the properties of the progenitor star, as first done for SN 1987A (Gilmozzi et al. 1987). Since the stellar luminosity is determined by the mass of the core, and the mass of the core is determined by the initial mass of the progenitor this is a fairly robust approach if there is sufficient data to well-determine the luminosity (although the mass at the time of explosion cannot be well-constrained, see Farrell et al. 2020). The challenge is that this must be done in distant (∼1-10 Mpc) galaxies and largely depends on the existence of multi-band archival Hubble Space Telescope data for robust results. The pro-
genitors of Type IIP supernovae are red supergiants with an upper mass limit that is consistent with the theoretical explosion studies (Smartt et al. 2003, Smartt 2009, Smartt 2014), although there are rebutted (e.g., Kochanek et al. 2014, Kochanek 2024, Beasor et al. 2020) counterarguments (e.g., Walmswell & Eldridge 2014, Girod et al. 2014, Davies & Beasor 2020). Less is known about the progenitors of Type Ibn supernovae because they are generally undetected, which likely implies that in most cases the envelopes are stripped by binary processes (e.g., Eldridge et al. 2013, Folatelli et al. 2016, Johnson et al. 2017, Kilpatrick et al. 2021). Unfortunately, the nature of the compact remnant formed in these systems will likely always be unknown.

Failed supernovae can be found by searching for stars which disappear independent of the nature of any associated transient (Kochanek et al. 2008). A search for failed supernovae using the Large Binocular Telescope (Gerke et al. 2014, Adams et al. 2017b, Neustadt et al. 2021) has identified one excellent candidate (Gerke et al. 2013, Adams et al. 2017a, Basinger et al. 2020) and a second, weaker candidate (Neustadt et al. 2021). As expected, the progenitor of the strong candidate was a massive RSG, and finding one candidate implies a fraction of core collapses leading to failed supernovae consistent with the current theoretical predictions.

The primary alternative to searching for individual progenitors is to use the local stellar population to infer the probable mass of the progenitor. This has been done for supernova remnants in the Magellanic Clouds (Badenes et al. 2009, Auchettl et al. 2019) and in nearby galaxies (e.g., Jennings et al. 2012, Jennings et al. 2014, Díaz-Rodríguez et al. 2018, Williams et al. 2018, Williams et al. 2019, Díaz-Rodríguez et al. 2021, Koplitz et al. 2021). Except for Williams et al. (2018) and Díaz-Rodríguez et al. (2021), which examine stellar populations near known supernovae, these are studies of the stellar populations near supernova remnants. The primary advantage of this method is that it can be applied to large numbers of supernova remnants or historical supernovae compared to the numbers of directly observed progenitors. For the Magellanic Clouds, several of the remnants are associated with neutron stars (N40, N158A and possibly SN 1987A in the LMC, and 1KT6 and 1E 0102.2−7219 in the SMC, see Badenes et al. 2009, Auchettl et al. 2019), so the outcome of the explosion is also known.

There are also several disadvantages. First, unless the local stellar population has a single well-defined starburst, the method does not provide individual well-constrained masses and so is best suited for making statistical models of the progenitor distribution. Second, the nature of the supernova is unknown for SNRs, so, for example, one cannot separately investigate the progenitors of Type IIP and Type Ibn supernovae. No SNR studies can directly address the deficit of more massive RSG progenitors to Type IIP supernovae because the supernova types are unknown. Third, the life time and detectability of the SNR has some dependence on the nature of the explosion (e.g., Sarbadhicary et al. 2014, Jacovich et al. 2023) which will introduce some bias into the results. Most, but not all, of these studies have supported a deficit of higher mass SN progenitors. The progenitor mass distribution models used to date in these studies are simple functional forms that do not resemble current theoretical expectations, so it is difficult to evaluate the degree to which they agree or disagree with these expectations.

With the advent of Gaia (Gaia Collaboration et al. 2014, Gaia Collaboration et al. 2021), it is now possible to apply this second method to Galactic supernova remnants if the distance to the remnant is known and the extinction is not severe. The present number of such systems is small, primarily because so few supernova remnants have well-constrained distances. As with extragalactic SNRs, the supernova type will generally be unknown, but, unlike extragalactic SNRs, the compact object outcome of the explosion frequently is known. Because the Galaxy is so well-surveyed from the mid-IR into the ultraviolet, it will generally be possible to characterize the individual stars extremely well, with well-determined individual stellar luminosities, temperatures and extinctions. In many cases, the brighter stars will also have spectroscopic classifications. Here we demonstrate this for the Vela pulsar (PSR J0835−4510, PSR B0833−45, Large et al. 1968), which is so nearby (280 pc, Dodson et al. 2003) that many of the massive stars near it are visible to the naked eye. We describe the selection of the stars and spectral energy distribution (SED) models of the more luminous stars in §2. We analyze these stars to estimate the likely mass of Vela’s progenitor in §3, and we discuss the results and future prospects in §4.

2 SELECTING THE STARS

We select the stars from the Gaia EDR3 catalog (Gaia Collaboration et al. 2016, Gaia Collaboration et al. 2021), requiring them to have parallaxes, proper motions and all three Gaia magnitudes. We apply no restriction on the RUWE statistic for the quality of the parallax. We adopt the position (J2000 08:35:20.61149 ± 0.00002, −45:10:34.8751 ± 0.0003), parallax (ϖ = 3.5 ± 0.2 mas) and proper motions (μα = −49.68 ± 0.06 and μδ = 29.9 ± 0.1 mas/year) of the pulsar from Dodson et al. (2003). The parallax is sufficiently accurate that it is essentially unaffected by Lutz-Kelker bias (see Verbiest et al. 2012). The spin down age of Vela is 11.3 kyr, although Lyne et al. (1996) argue that the braking index implies a larger age. The proper motions combined with the offset from the center of the remnant imply an age of 18000 ± 9000 years based on the 25 ± 5 arcmin offset of the pulsar from the center of the remnant (Aschenbach et al. 1993). Unfortunately, Aschenbach et al. (1993) do not report their estimated position for the center, but if we adopt an age of T = 20000 years we can estimate the position of the explosion from the position shift of (+17, −10) arcmin. The remnant itself has a diameter of approximately 8.3 degrees, so the shift is small compared to the scale of the remnant and the size of our search region. We select the stars in a region centered on the shifted equatorial position of (128.84°, −45.18°) where we have reduced the coordinate precision due to the uncertain age.

The next question is the size of the region to extract around Vela to obtain a representative stellar population. The studies of the regions around supernovae and SNRs in nearby galaxies have almost uniformly used a region 50 pc in radius based on the argument that stars form in compact clusters (~ 1 pc, Lada & Lada 2003), drift apart at low rela-
Figure 1. Color-magnitude diagram without extinction corrections for the stars with $M_G > 0$ mag and within $R < 125$ pc of Vela. The background contours are the maximum likelihood model for the stellar density including extinction with solid (dashed) contours at higher (lower) densities that are spaced by factors of 3. The red curves are Solar metallicity PARSEC isochrones with ages of $10^{8.5}$ (bottom, dashed), $10^{8.0}$ (dashed) $10^{7.5}$ (solid), $10^{7.0}$ (solid) and $10^{6.0}$ (top, solid) years. The maximum mass for the $10^{7.5}$ year isochrone is $9.1 M_\odot$, so only the solid isochrones still have stars which will explode as supernovae. The isochrones are shifted by the mean extinction of $E(B-V) = 0.057$ mag.

tive velocities ($\sim$ km/s), and that stars which explode after their parent binary was disrupted by a supernova have only modest velocities.\cite{Eldridge2011,Renzo2019}. With Gaia, we can simply consider this question empirically. In this section we consider the three dimensional geometry we use for Vela, and in §4 we consider the two-dimensional projected geometry of extragalactic analyses.

We started by extracting all stars within $R = 250$ pc of Vela. If the pulsar is at a distance of $D = 286$ pc, a sphere of radius $R$ subtends a maximum angle of $\theta = \sin^{-1} R/D \approx 62$ deg relative to its center. We select stars with $\theta < 62$ deg, $1.87 < \pi < 28.6$ mas, which corresponds to $\pm 250$ pc around the pulsar distance, and $G < 9.5$ mag. This will include all stars with $M_G \lesssim 0$ mag since the extinctions are small. At this magnitude limit we are including all $M \gtrsim 5M_\odot$ stars and the more luminous, evolved, lower mass stars. The initial search yields $\sim 55,000$ stars, of which $\sim 37000$ are within $R = 250$ pc of the pulsar, and 3160 are brighter than $M_G < 0$ mag.

The bright magnitude limit of Gaia at $G \gtrsim 3$ mag can be a problem because the most luminous stars may not be present in the Gaia catalog. We searched the Hipparcos \cite{Perryman1997}, using the updated astrometric solution from \cite{vanLeeuwen2007} and the Bright Star \cite{Hoffleit1993} catalogs for any such stars in the search volume, finding nine Hipparcos stars: HIP 30324 ($\beta$ Cma), HIP 33579 ($\epsilon$ Cma), HIP 39953 ($\gamma^2$ Vel), HIP 41037 ($\epsilon$ Car) HIP 44816 ($\lambda$ Vel), HIP 66657 ($\epsilon$ Cen) HIP 68702 ($\zeta$ Cen), and HIP 81173 ($\alpha$ TrA). Since $\gamma^2$ Vel is in a wide binary \cite{Tokovinin2018} with $\gamma^1$ Vel (HD 68243), we use the Gaia parallax of $\gamma^1$ Vel for $\gamma^2$ Vel. For the other stars we adopt the updated Hipparcos parallaxes. Including the bright Hipparcos stars, there are $N = 3169$ stars with $M_G < 0$ mag within $R = 250$ pc of Vela. Figure 1 shows the distribution of the $R < 125$ pc stars in absolute magnitude $M_G$ and color $B_P - R_P$ (with no extinction corrections) as compared to Solar metallicity PARSEC \cite{Bressan2012,Marigo2013,Pastorelli2020} isochrones with ages of $10^{8.6}$, $10^{8.0}$, $10^{7.5}$, $10^{7.0}$ and $10^{6.5}$ years. For the bright Hipparcos stars we used the SED fits described below to synthesize the Gaia magnitudes.

To explore optimizing the region from which we select stars, we only want to consider the younger, massive stars. The main contaminants are lower mass red giants, which we can largely remove by considering only stars with $M_G < 0$ for $B_P - R_P < 0.6$, $M_G < -2.0$ for $0.6 < B_P - R_P < 1.8$, and $M_G < -3.5$ for $B_P - R_P > 1.8$. Only a small fraction of the stars have Gaia DR2 radial velocities, so we assigned a random line of sight velocity with a dispersion of 3.0 km/s based on the velocity dispersion derived from the proper motions of the stars within 50 pc of Vela (see below).

In our present analysis we are selecting the stars in three dimensions, so we want to explore the effect of changing the radius of the selection sphere. We can estimate the completeness and contamination of the selection by examining the relative positions of the stars today and in the past. We start by taking the stars near the pulsar and determining where they were 10, 5, 3, 2, 1, 0.5, 0.1, 0.05, 0.01, 0.005, 0.001 years ago, we can estimate the completeness and contamination. The completeness is the fraction of stars in the "past sphere" that were not in the "present sphere" that were not in the "past sphere". The contamination is the fraction of the stars in the past. The contamination is the fraction of the stars in the past that were not in the "present sphere" that were not in the "past sphere". The completeness will be lower if we include a random motion for the progenitor.

Following the extragalactic studies, we first considered a 50 pc sphere. This sphere around Vela today contains 19 of these young, high mass stars. After subtracting their mean tangential velocities, they have a two-dimensional (2D) velocity dispersion of 4.2 km/s defined by half the width of the velocity range encompassing 68% of the stars. As we expand the radius of the sphere, the number of stars rises rapidly to 152, 411, 757 and 1160 within 100, 150, 200 and 250 pc, and the 2D velocity dispersion rises slowly to 5.4, 6.7, 6.7 and 7.9 km/s, respectively. We used the 4.2 km/s dispersion derived from the proper motions to set the $4.2/\sqrt{2} = 3.0$ km/s dispersion of the randomly assigned line of sight velocity. The three dimensional velocity dispersion is then 5.1 km/s, so the typical typical massive has a random motion of $\pm 50$ pc in the lifetime of a $\sim 20M_\odot$ star ($\sim 10^7$ years) and $\pm 150$ pc in the lifetime of a $\sim 10M_\odot$ star ($\sim 10^{5.5}$ years).

If we place a sphere at the median position of these stars 10$^7$ years ago, we can estimate the completeness and contamination. The completeness is the fraction of stars inside a sphere of some radius today that are inside a sphere of some other radius centered at the median position of the stars in the past. The contamination is the fraction of the stars in the "past sphere" that were not in the "present sphere".
sphere”. For a 50 pc sphere today, 4, 12, 16 and 18 of the 50 pc sphere today. So the completenesses are 21%, 63%, 84% and 95%, while the contamination rates are 71%, 84%, 92% and 95%. Basically, since the typical random motion corresponds to moving 50 pc in 107 years, a sphere of comparable size must suffer from poor completeness and significant contamination. If we increase the size of the present sphere to 100 pc, the completenesses in past spheres of radius 100, 150, 200 pc are 36%, 68% and 84%, respectively, and the contamination rates are 5%/75%, 16%/79%, 26%/88% and 47%/89%, respectively (3%/61%, 9%/61%, and 22%/58% for 100 pc today; 7%/15% and 15%/25% for 150 pc today).

Completeness and contamination are, or course, a trade off – there is no right answer. We will present all of our results for a radius of 125 pc. We were originally going to use 100 pc but the most massive star near Vela, γ2 Vel, lies just outside a 100 pc sphere, so we increased the radius to 125 pc to double the volume and include γ2 Vel. For the final results on the probable age and mass of Vela’s progenitor, we will present the results for a range of radii.

We fit the spectral energy distributions (SEDs) of the more luminous stars in the 125 pc sphere to estimate their luminosity, temperature and extinctions. We also fit the bright Hipparcos stars to synthesize their Gaia magnitudes. The SED fits are moderately labor intensive in terms of collating the data, so we did not model all the lower luminosity stars. We initially selected all stars with $M_G < -2$ ($M_G < -3.5$) for $B_P - R_P < 1.8$ ($> 1.8$), where the higher luminosity limit for redder stars eliminates lower mass red giants. While the SEDs showed no need to include circumstellar dust, we used the same methods as in [Adams et al. 2017], running DUSTY [Elitzur & Ivezid 2001] inside a Markov Chain Monte Carlo (MCMC) driver to both optimize the fits and then estimate the uncertainties. We used Castelli & Kurucz 2003 model atmospheres for all but the coolest stars where we used MARCS (Gustafsson et al. 2008) model atmospheres. We used near-IR data from 2MASS [Cutri et al. 2003]. The optical data primarily came from Johnson et al. [1966] and Tonry et al. [2018], supplemented by Cousins [1971], Ducati [2002], Mermilliod [1977], Morel & Magnenat [1978], NOMAD [Zacharias et al. 2005], and Neckel & Klare [1984]. Almost all of the hot stars had UV data extending to ~1500 Å from either Thompson et al. [1978] or Wesselius et al. [1982].

We used temperature priors based on the reported spectral types and weak extinction priors. The temperature prior widths were roughly one spectral type (so B1 to B3 for a B2 star) and ±0.1 mag for $E(B-V)$. For extinction priors, we use the three dimensional combined19 models, which include the Drimmel et al. [2003], Marshall et al. [2006] and Green et al. [2010] models to provide estimates for any sky position. We extracted the V band extinction, and then used an $R_V = 3.1$ extinction law to convert the V band extinction to those for the $G$, $B_P$ and $R_P$ bands. For most stars, the SEDs could only modestly improve the spectral temperature estimates but strongly constrained the extinction. The agreement with the extinction estimates was generally good, except when the extinction estimate was high ($E(B-V) \geq 0.1$). In these cases, the SED models generally required much less dust. With this caveat, we will use the extinctions to model the effects of extinction for the full sample.

Table 1 gives the goodness of fits, temperature, luminosity, mass, age, separation from estimated explosion center and some comments for the stars with $L_\star > 10^{3.5}L_\odot$. The individual masses and ages are simply the range of PARSEC isochrone ages and masses where the luminosity and temperature are within twice the estimated uncertainties of the fitted values with a minimum uncertainty of 0.02 dex. The ages and masses are strongly correlated - the maximum masses correspond to the minimum ages and vice versa. Except for γ2 Vel, they are all less massive than ~15M⊙ and older than ~10^7 years even for the upper (lower) limits on the masses (ages).

While many of the stars are binaries (see Table 1), the extra light from the secondary seems to have little consequence for the SED fits. This is not very surprising because B stars are still in the regime where the mass-luminosity relation is fairly steep and a modestly lower mass companion will not greatly perturb the SED. For example, consider the most luminous star, γ2 Vel, which is an O star plus Wolf-Rayet (WR) star binary. γ2 Vel is an interferometrically resolved double lined spectroscopic binary with present day masses of (28.5 ± 1.1)M⊙ and (9.0 ± 0.6)M⊙ for the O star and the companion WR star, respectively (North et al. 2007). While our SED fit finds a higher total luminosity, most of the difference is due to both the Gaia EDR3 distance (where we used the distance to the wide binary companion γ1 Vel and our extinction estimate being larger than those used by North et al. 2007). Still, our rough individual mass estimate of 25.3-27.3M⊙ agrees reasonably well with their dynamical measurement. North et al. (2007) estimate that only 22% of the V-band light comes from the WR star, so the SED fit itself is not strongly biased by the WR companion.

3 THE PROGENITOR OF VELA

The striking property of Figures 1 and the models in Table 1 is the marked absence of very young stars or massive stars with the exception of γ2 Vel. All of the other stars are only consistent with populations older than ten million years, corresponding to maximum progenitor masses $\lesssim 15M_\odot$. The next step is to use these stars to estimate the mass of the progenitor of the Vela pulsar. Here we will model the Gaia color-magnitude distribution to estimate the numbers of stars as a function of age. As discussed in §2, we present all of the results for a 125 pc sphere around Vela, and the estimated age/mass of the progenitor for regions from 100 to 200 pc in radius.

We will assume a Salpeter [1955] initial mass function (IMF) with a minimum mass of $M_{min} = 1M_\odot$ since we are not interested in the lower mass stars. If the star formation rate ($M_\star$/year) for $M > M_{min}$ stars is SFR, then the rate of forming stars is
\[ \frac{dN}{dt} = \frac{(x-2)SFR}{M_{\text{min}}^2} \left( \frac{M}{M_{\text{min}}} \right)^{-x} \]  

(1)

with \( x = 2.35 \) and a mean mass of \( \langle M \rangle = (x-1)M_{\text{min}}/(x-2) \). We divide the star formation history into logarithmic time intervals \( t_{\text{min},i} < t < t_{\text{max},i} \) with \( \Delta t_i = t_{\text{max},i} - t_{\text{min},i} \).

Assuming the star formation rate \( SFR \) in the interval is constant, the number of stars that \( M > M_{\text{min}} \) stars formed is

\[ N_i = \frac{SFR_i \Delta t_i}{\langle M \rangle} \]  

(2)

The number of stars formed in this period which die in a short time interval \( \Delta t \) today is

\[ N_i \frac{\delta t}{\Delta t} \left[ \left( \frac{M_{\text{min}}}{M_{\text{min}}} \right)^{1-x} - \left( \frac{M_{\text{max}}}{M_{\text{min}}} \right)^{1-x} \right] = N_i S_i \delta t \]  

(3)

where \( M(t) \) is the most massive surviving star on the isochrone, and \( S_i \delta t \) is the fraction of \( M > M_{\text{min}} \) stars that died in the last \( \delta t \) years. This expression is explicitly assuming single star evolution. We used 8 temporal bins spanning.
6.4 < log \( t \) < 8.0, bin widths of 0.2 dex and use the number \( N_i \) of \( M > M_{\text{min}} \) stars formed as the variable to be determined.

If the global IMF is [Salpeter 1955] down to \( 0.5 M_\odot \) and then flattens to \( M^{-1.3} \) from \( 0.08 M_\odot \) to \( 0.5 M_\odot \) [Kroupa 2001], then the \( M > M_\odot \) stars represent 9.1\% of the stars formed. The global mean mass is 0.61\( M_\odot \), so for each \( M > M_\odot \) star formed, the total mass of new stars is 6.7\( M_\odot \). Local estimates of the mean stellar mass density are 0.04\( M_\odot \) pc\(^{-3}\) (e.g., Flynn et al. 2006), so we should find \( \sum N_i \approx 6 \times 10^4 \). If we use \( 2\pi R_d^2 H \) with \( R_d = 3 \) kpc and \( H = 0.1 \) kpc as the volume of the Galaxy, forming ten \( M > M_\odot \) stars per megayear in a 125 pc sphere corresponds to a global star formation rate of \( \sim 0.04 M_\odot /\text{year} \).

We start by building density maps \( \rho_i^{jk} \) in absolute magnitude \( M_G \) (index \( j \)) and color \( B_P - R_P \) (index \( k \)) for each time interval \( i \). We use Solar metallicity PARSEC isochrones sampled at \( \Delta \log t = 0.01 \) dex. For each density map \( i \) we carry out \( N_{\text{trial}} \) trials. We uniformly select a time between \( t_{\text{min},i} \) and \( t_{\text{max},i} \), which corresponds to assuming a constant star formation rate for each bin, randomly draw an initial stellar mass from the IMF, and use the isochrones to determine the absolute magnitude and color if a star of this mass still exists.

For the magnitude range we consider, the uncertainties in the Gaia magnitudes are negligible. Similarly, the median parallax uncertainty of 0.027 mas is also unimportant given that the smallest parallax we consider is 2.43 mas. The median \texttt{mwdust} extinctions increases as \( E(B-V) = 0.19(d/\text{kpc}) \) with distance \( d \) from the Sun. The width of the distribution is approximately 0.13(d/\text{kpc}). Since the \texttt{mwdust} estimates agreed reasonably well with the extinction estimates from the SED fits, we randomly assigned each trial the \texttt{mwdust} extinction of one of the \( M_G < 0 \) mag stars.

If the extincted trial star has \( M_G < 0.0 \) mag, we add \( N_{\text{trial}}^{i} \) to the appropriate cell of \( \rho_i^{jk} \). The maps span a finite range of color \(-0.75 < B_P - R_P < 3.5 \) and absolute magnitude \((0.0 > M_G > -8.0) \) so trial stars that fall outside the color range or are brighter than \(-8.0 \) mag are placed at the bin edge. This preserves the total probability for \( M_G < 0.0 \) mag stars. As we build the maps, we also build a binned mass distribution of the \( M_G < 0.0 \) mag stars, \( D_i^j \) for mass bin \( j \). For \( M_G < 0.0 \) mag we are including almost all \( M > 5 M_\odot \) stars, and then only mass-dependent portions of the post-main sequence lifetimes of the lower mass stars.

With these definitions, the number distribution of stars in magnitude and color brighter than the selection limit from time period \( i \) is \( N_i \rho_i^{jk} \) and \( N_i \sum_k \rho_i^{jk} = N_i F_i \) is the number of stars still living and passing the selection criterion. \( F_i \) is the fraction of \( M > M_{\text{min}} \) stars which are more luminous than \( M_g > 0 \) mag. The expected number of stars in a color/absolute magnitude bin is

\[
e_{jk} = \sum_i N_i \rho_i^{jk}.
\]

If we now distribute the \( N \) actual stars over the grid, the ob-

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**Figure 2.** Age distribution \( N_i F_i \) of the modeled stars. The points show the median number of stars associated with each age bin and the 90\% confidence range. The horizontal error bars span the bin widths, and the mass range corresponding to the more massive age bins is listed. The solid red curves shows the median integral distribution and the dashed curves show its 90\% confidence range. All uncertainties are highly correlated. The integral distribution converges exactly to the number of stars because we are determining how to distribute the modeled stars over the age bins.

**Figure 3.** Inferred numbers \( N_i \) of \( M > M_{\text{min}} = M_\odot \) stars formed for each age bin. This corresponds to the number of modeled stars shown in Figure 2 divided by the fraction \( F_i \) of \( M > M_{\text{min}} \) stars which have \( M_G > 0 \) mag. The points show the median number of \( M > M_{\text{min}} \) stars associated with each age bin and the 90\% confidence range. The horizontal error bars span the bin widths, and the mass range corresponding to the more massive age bins is listed. All uncertainties are highly correlated.
Figure 4. Rate of forming $M > M_{\text{min}} = M_\odot$ stars per million years for each age bin. This corresponds to the number of $M > M_{\text{min}}$ stars $N_i$ shown in Figure 3 divided by the temporal bin width $\Delta t_i$. The points show the median star formation rate associated with each age bin and the 90% confidence range. The horizontal error bars span the bin widths, and the mass range corresponding to the more massive age bins is listed. All uncertainties are highly correlated.

The logarithm of the likelihood for all $N$ stars is

$$\ln L = \sum_{\text{stars}} \ln \left( \frac{n_{ij}^{e_{ij}}}{n_{ij}!} \right) - \sum_{\text{all}} r e_{ij}$$

where the first term is the sum over bins containing stars and the second is the sum over all bins. Note that the factorial $n_{ij}!$ can be discarded since the calculation depends only on likelihood differences and not the absolute likelihood. Putting trial stars falling off the grid when constructing the distributions on the bin edges ensures that the second sum is correct.

In Equation 5 we have also introduced a “renormalization” factor $r$. Equation 5 with $r = 1$ still includes the Poisson uncertainties from the total number $N$ of stars being modeled. For the problem of estimating the progenitor mass, however, we need the relative probabilities (i.e. ratios) of the numbers of stars in the age bins, not their absolute values, and the ratios are unaffected by Poisson fluctuations from the finite number of stars. We solve this problem by optimizing the likelihood with respect to the renormalization factor to find that

$$r = N \left[ \sum_{\text{all}} e_{ij} \right]^{-1},$$

which we then use to renormalize $N_i \rightarrow r N_i$. With this renormalization, $\sum_{\text{all}} e_{ij} \equiv N$ and we have effectively converted the Poisson likelihood into a multinomial likelihood for how to divide the $N$ stars over the age bins.

Operationally, we optimize the likelihood and estimate the uncertainties using Markov Chain Monte Carlo (MCMC) methods with the log $N_i$ as the variables. Once trial values of log $N_i$ are selected, they are renormalized before computing the likelihood. Some age bins were susceptible to log $N_i \rightarrow -\infty$ (i.e., $N_i$ arbitrarily close to zero), so we added a weak prior that the star formation rates of adjacent temporal bins should be similar by adding

$$\lambda^{-2} \sum_i \left[ \ln \left( \frac{N_i \Delta t_i}{N_{i+1} \Delta t_{i+1}} \right) \right]^2$$

with $\lambda = 6.91$ to the likelihood. This adds a penalty of unity to the likelihood if adjacent bins have star formation rates ($SFR_i \propto N_i/\Delta t_i$) that differ by a factor of 1000. This is just to prevent numerical divergences and has no significant effect on the results.

Figure 1 shows contours for the numbers of stars as a function of luminosity and temperature for the maximum likelihood model. Not surprisingly the maximum density lies along the main sequence of B stars. The density contours follow the stellar distribution closely. There are a few red giants in very low density regions. This may mean that there some stars with higher extinctions than our model, proba-
Stars would be another \( \sim \) stars, the 607 we modeled. and the total number of \( M > M_a \) as a function of age. As expected, the total number of stars associated with the older bins is much larger. Figure 3 show the number of stars dying in the last 10 years. The number of stars dying in the last 10 years is given by the integral distribution and the dashed curves show its 90% confidence range. The arbitrary renormalization procedure, the numbers add up exactly to 1. The solid red curves shows the median integral distribution and the dashed curves show its 90% confidence range. The horizontal error bars span the bin widths, and the mass range corresponding to each age bin is listed. The implied stellar mass density of \( (0.056 \pm 0.019) M_\odot \) pc\(^{-3} \) is remarkably close to the local estimate of \( 0.05 M_\odot \) pc\(^{-3} \) (Flynn et al. 2006) given the huge correction required to go from the number of \( M_G > 0 \) mag stars to the total mass of stars - for the oldest bin, the \( \sim 50 \) modeled \( M_G > 0 \) mag stars represent some \( \sim 20,000 \) \( M > M_\odot \) stars which then correspond to some \( \sim 200,000 \) stars in total.

Finally, Figure 4 shows the star formation rates for each temporal bin as the number of \( M > M_\odot \) stars formed per 10\(^6 \) years. As discussed above, a formation rate of 10 \( M > M_\odot \) stars per million years corresponds to a global Galactic star formation rate of order 0.04\( M_\odot \)\,year\(^{-1} \), so the peak star formation rate of \( \sim 0.3 \)\( M_\odot \)\,year\(^{-1} \) on a global basis is not impressive. The peak is, however, again found in the 10\(^7\)-10\(^8\) year bin. The star formation rates in the younger bins are at least an order of magnitude lower, with even fewer new stars because the associated times \( \Delta t_i \) become shorter (i.e. the drop off in Figure 5 is sharper than in Figure 4).

Figure 5 shows the model for the integral distribution of the selected stars in mass

\[
D^i = \sum_i N_i D_i^i 
\]

(8)

where the \( D_i^i \) are the mass distributions associated with each temporal bin. As expected from the distributions in Figures 1 the region contains few higher mass stars. We also show the integral distribution of the mass estimates from the SED models in Figure 6. Broadly speaking they are in good agreement, although the results from the CMD models track the lower mass limits much more closely than the upper mass limits. As noted earlier, at roughly constant luminosity and

\[7.4, 7.6]
temperature, there is a strong correlation between age and mass for these main sequence B stars in the sense that the minimum mass estimates correspond to the maximum ages and vice versa. The CMD models strongly disfavor having significant numbers of stars with the young ages associated with the maximum mass estimates and strongly favor ages corresponding to the minimum mass estimates and so track the minimum mass estimates. The CMD models constrain the age distribution better than the SED models of individual stars.

The outlier in Figure 4 is $\gamma^2$ Vel. The model mass distribution on the CMD predicts only $\sim 0.3 (\pm 0.1)$ stars with $M > 20M_{\odot}$ ($> 30M_{\odot}$). The existence of $\gamma^2$ Vel is not a huge statistical anomaly, as the likelihood of having one or more such stars is $26\% \ (10\%)$. However, in the CMD (Figure 4), there are simply no other stars between where the $10^{-10}$ year isochrone (maximum mass $9.1M_{\odot}$) starts to turn off the main sequence and $\gamma^2$ Vel. The absence of these stars drives the model to make $\gamma^2$ Vel moderately unlikely.

Figure 6 shows the number of stars $N_iS_i \delta t$ (Equation 3) predicted to have died in the last $\delta t = 10^5$ years for each age bin. That the integral probability sums to near unity is happenstance – the distribution is not normalized. The probability for the ages leading to supernovae is dominated by the age range corresponding to initial masses of $8.1-10.3M_{\odot}$. Note that for the range of ages producing supernovae, the expected number of deaths in the last $10^5$ years is only $\sim 0.1$ and so the time scale for this volume to produce a supernova is $\delta t \approx 10^5$ years, far longer than the life time of an SNR. This is not a statistical problem – we chose this volume because it contained an SNR. To estimate $\delta t$ we would have to analyze a much larger volume chosen without using any prior knowledge of the number of encosed remnants.

Figure 6 also shows what the prediction would be if the star formation rate was constant across all age bins, roughly normalized to the intermediate age bins where the estimated star formation rates are nearly constant (Figure 4). The four youngest and two oldest bins have lower estimated SFRs, and so fewer stars are predicted to have died in the last $10^5$ years, while the $10^{-7}-10^{-6}$ year bin has a higher SFR and more predicted deaths. The difference between the two curves represents the information added by using the local stellar population to infer the star formation history.

The probability of a star dying in the last $\delta t = 10^5$ years is dominated by the older bins and the volume is likely to contain a number of young white dwarfs. Out of curiosity we did a cursory search for candidates. Based on the MIST (Dotter 2014; Choi et al. 2016) evolutionary tracks, a $< 10^3$ year old white dwarf should be a very hot star with a luminosity $\sim 10^4L_{\odot}$. The Gaia EDRE source ID#5319832121597913084 is the bluest and most luminous source near the tip of the usual white dwarf cooling sequence. It is flagged as a very high probability white dwarf candidate by Gentile Fusillo et al. (2019) but with no estimates of its physical properties. There are no UV or spectroscopic observations of it, but for an assumed temperature of 40,000 K it would have a luminosity of $\sim 2L_{\odot}$. Since the luminosity scales linearly with the temperature on the Rayleigh-Jeans tail of the SED, this star has to be significantly older than $10^5$ years even at twice the temperature. There are five similarly blue but $\Delta M_G \sim -3$ mag more luminous stars (#5592257426113535104, #541100259497913392, #544202404423183242, #5512856125193586176, and #559780553619327360) whose luminosities could be in the right range. Three of them are spectroscopically classified as hot sub-dwarfs (#5592257426113535104, Garrison & Hiltner 1973; #544202404423183242, Barlow et al. 2013; #559780553619327360, Kilkenny et al. 1988) one (#5411002594979483392) is spectroscopically classified as an A0 star (Nesterov et al. 1993) but this difficult to reconcile with its location in the CMD, and #5512856125193586176 has no spectroscopic classifications. Possibly one of these latter two sources is a very young white dwarf masquerading as a hot subdwarf.

To produce a final constraint on the mass of Vela’s progenitor we must consider three remaining issues. First, we have to put a minimum mass in by hand. When analyzing a single region around one target, we cannot determine a minimum mass for explosion. This requires analyzing many such regions both with and without SNRs. We must impose a minimum mass by simply dropping the older age bins. The obvious choice is to keep only the $10^{-6}$-$10^{-4}$ year, with its maximum masses at death of $8.1-10.3M_{\odot}$, and younger bins. For single star evolution, this is the correct mass range for the cutoff. With binary evolution the next older bin can contribute through mergers of longer lived, lower mass stars (see, e.g., Zapartas et al. 2017). Retaining this next older bin would only strengthen our final conclusion that the progenitor was significantly less massive than $20M_{\odot}$. The change would be modest because many fewer stellar deaths are expected from this age bin than from the $10^{-7}$-$10^{-6}$ year bin (see Figure 6).

In our formalism, the number of stellar deaths is $N_iS_i \delta t$ where $S_i$ is independent of $\delta t$. For our final result we want the relative probabilities of the age bins with no dependence on $\delta t$. The probability that the progenitor came from bin $i$ and no other bin $j$ is

$$P(i|\delta t) = N_iS_i\delta t \exp(-N_iS_i\delta t)\Pi_{s_{ij}}\exp(-N_jS_j\delta t) \quad (9)$$

The total probability summed over all the bins is

$$P_{tot} = \sum_i P(i|\delta t) = \delta t \left[ \sum_{all} N_iS_i \right] \exp(-\delta t \sum_{all} N_iS_i) \quad (10)$$

and thus the normalized probability for each bin of

$$P_{tot}^{-1} P(i|\delta t) = N_iS_i \left[ \sum_{all} N_iS_i \right]^{-1} \quad (11)$$

is independent of $\delta t$ as desired. Basically, this just corresponds to normalizing the integral probability distribution so that the total probability is unity.

Finally, we have a maximum likelihood solution and all the MCMC samples, each of which represents a realization of the integral probability distribution. We could go to each age bin, sort these distributions and report a median and some range, say 90% confidence, but it is unclear how to interpret this. What does it mean to say there is a 5% chance that there is a 10% chance that the progenitor was younger than the age of some bin? There really should be only one distribution which incorporates this information. We are really combining the $N_{MCMC}$ results of the MCMC chains,
each of which has a probability of \( N_{\text{MC}}^{-1} \), and each trial predicts a probability for the age of the progenitor. The way to combine them is to sum the probability the trial predicts for the age bin weighted by the probability of the trial—in short, the final probability distribution is simply the average of the MCMC samples.

Figure 4 shows these final probability distributions as a function of the radius \( R \) of the sphere used to select the stars. Recall that the results so far have all been for \( R < 125 \) pc. The maximum likelihood age distributions modestly favor older, lower mass progenitors compared to these distributions. For \( R < 100 \) pc, a low mass progenitor is very strongly favored with a 94% probability of it coming from the lowest mass bin (8.1-10.3\( M_\odot \)). However, as we discussed in §2, this sphere probably only contains \( \sim 2/3 \) of the stars born within a similar radius. If we increase the radius to \( R < 125 \) pc, the structure of the distribution changes considerably, and this is entirely driven by the inclusion of \( \gamma^2 \) Vel. The probability of the oldest age bin is still high (90%), but the probability of an age bin corresponding to a progenitor more massive than \( 20M_\odot \) increases by almost an order of magnitude. None the less, the probability of a progenitor less massive than \( 20M_\odot \) is still 95%. Expanding the sphere still further primarily increases the probability of the 13.6-19.3\( M_\odot \) and 10.3-13.6\( M_\odot \) progenitor bins relative to the 8.1-10.3\( M_\odot \) bin. The probability of being less massive than \( 20M_\odot \) is still 90%.

In fact, \( \gamma^2 \) Vel is associated with a concentrated cluster of pre-main sequence stars with a very low velocity dispersion (e.g., Franciosini et al. 2018). This means that associating the progenitor of Vela with the formation of \( \gamma^2 \) Vel and its cluster requires the progenitor to have been a runaway star. To explore this we used the fiducial runaway model from Renzo et al. (2019) and estimated the distance the surviving stars from disrupted binaries could travel in the time left for their current evolutionary phase. Since we now have an isolated star, this will be close to the remaining life time of the star. Because of mass transfer, we examined the fraction of stars which could travel more than 100 pc (the distance from \( \gamma^2 \) Vel to the pulsar) in bins of either the zero age main sequence (ZAMS) mass or the mass after the binary is disrupted.

For the ZAMS mass and no restriction on the mass of the star which died to disrupt the binary, the chances of traveling 100 pc were significant only for \( 10-15M_\odot \) (20%) and 15-20\( M_\odot \) (5%) stars. Stars with higher post-disruption masses could do so because they are initially lower mass stars that were mass gainers when the primary began to evolve. Even so, only 7.6%, 2.7%, and 2.2% of stars with post disruption masses of 20-25, 25-30, and 30-35\( M_\odot \) could travel 100 pc. Demanding a high (\( M > 30M_\odot \)) ZAMS mass primary helps only modestly. Thus, a volume including \( \gamma^2 \) Vel does significantly increase the probability of a higher mass (\( \gtrsim 20M_\odot \)) progenitor, but a Vela progenitor formed in the cluster associated with \( \gamma^2 \) Vel would (a) have to be a runaway star from a disrupted binary, and (b) would have to have a statistically unlikely runaway velocity.

4 DISCUSSION

The environment of the Vela pulsar is dominated by B stars with only one nearby O star, \( \gamma^2 \) Vel. If we consider only stars within \( R < 100 \) pc of Vela, the most likely (95%) age range for its progenitor is \( 10^{-4} \text{–} 10^{-6} \) years corresponding to a mass range of 8.1-10.3\( M_\odot \). There is clearly a local burst of star formation associated with this age bin. For these ages and the observed velocity dispersions of the stars, a radius of \( R < 100 \) pc will not encompass all of the stars formed within 50-100 pc of the progenitor. Any larger sphere encompasses the most massive nearby star, the O star plus WR star binary \( \gamma^2 \) Vel. So for \( R < 125 \) pc, there is still a 90% probability of associating the progenitor with the \( 10^{-4} \text{–} 10^{-6} \) year age bin, but there is now a 5% chance of an age allowing masses > 20\( M_\odot \). However, \( \gamma^2 \) Vel is associated with a very low velocity dispersion cluster, so for the progenitor to be that massive it would also need to be a runaway star from a disrupted binary with an unusually high velocity based on the models of (Renzo et al. 2019).

We have assumed single star evolution models in this analysis. We know that Vela itself was not a binary or triple at the time of its death (Kochanek 2021, Fraser & Boubert 2013) down to companion mass limits \( \lesssim M_\odot \). This does not rule out the progenitor as a merger remnant or as an unbound secondary from a previous explosion. As a merger remnant or an unbound secondary that gained significant mass through mass transfer, we have underestimated the probability of a low mass progenitor because we imposed the minimum mass/maximum age limit by hand since it cannot be determined by analyzing a single system. The changes from including the next lower mass bin would not be huge, because the star formation rate estimated for this next bin is much lower than for the \( 10^{-4} \text{–} 10^{-6} \) year age bin.

As noted in the introduction, the two fundamental limitations to applying this method in the Galaxy are estimating the distance to the supernova remnant and extinction. There are three additional systems which can be analyzed easily. G180.0-01.7 is associated with the radio pulsar PSR J0538+2817, which has a VLBI parallax (Ng et al. 2007, Chatterjee et al. 2004). In Kochanek (2021) we examined the properties of the nearby luminous stars but did not carry out a formal analysis as done here for Vela. G205.5+0.005 (Monoceros Loop) and G284.3-01.8 both contain neutron star high mass X-ray binaries (Hinton et al. 2007, Corbet et al. 2011) and the stellar companions have Gaia parallaxes (see Kochanek 2021). Unfortunately, the interacting (probably) black hole binary SS 433 (see the review byMargon 1984) in G039.7-02.0 is likely too distant (\( \pi^{-1} = 8.5 \) kpc) to use Gaia parallaxes to trivially select stars in a \( \sim 100 \) pc sphere around the binary. The Gaia EDR3 parallax of SS 433 is also in strong (\( \sim 5\sigma \)) disagreement with the distances estimated from kinematic models of the relativistic jets (Blundell & Bowler 2004, Marshall et al. 2013). As discussed in Kochanek (2021), the success of Cha et al. (1999) in determining the distance to the Vela remnant based on the distance at which stars began to show absorption features from the supernova remnant provides a simple observational approach to better determining the distances to other remnants.

If we consider the 165 pulsars with parallaxes in the ATNF Pulsar Catalog (Manchester et al. 2005), the vast majority cannot be analyzed using this method because the formation region cannot be well-localized. In particularly, the only available age estimate is the spin down age which at best estimates the time of explosion to within a factor of two.
If we require that the projected distance traveled in the spin down age is less than 100 pc, only 10 pulsars are left after excluding Vela. Because the proper motions represent two components of the kick velocity while the motion along the line of sight contains only one component, the line of sight motions should be of less a problem. If we assume a typical neutron star kick velocity of 265 km/s (Hobbs et al. 2005), the typical line-of-sight distance traveled in the spin down time for the pulsars with transverse motions less than 100 pc ranges from 24 to 152 pc. If we require this line-of-sight motion for the pulsars with transverse motions less than 100 pc to be <100 kpc and restrict the parallax distance to be <2 kpc, we are left with four systems other than Vela (J0157+6212, J0633+1746, J0659+1414 and J2032+4127). This would be a sample biased towards supernovae with low kick velocities.

In the absence of good parallaxes, the alternative is to simply look at all the stars projected within a fixed projected separation from the SNR over some broad line of sight distance range consistent with estimates for the distance to the SNR. This is what is done for all the extragalactic analyses since there is no possibility of using parallaxes to remove the foreground and background contamination. However, while some of the external galaxies that have been examined are highly inclined (e.g., Andromeda at $\sim 13^\circ$), none have an unfavorable geometry for minimizing contamination as we face for examining Galactic SNRs. Which Galactic SNRs are suitable for such an analysis will depend on their Galactic coordinates.

Related to this is the question of completeness and contamination in analyses of stellar populations near extragalactic supernovae and remnants. We can use our nearly complete knowledge of the environment around Vela to evaluate the 50 pc projected search region used by Jennings et al. (2012) and subsequent papers. We again restrict ourselves to the more massive stars using the magnitude and color cuts described in §2. We transform the stellar positions to axes aligned with Galactic coordinates, select stars in a sphere around Vela, and then count stars using their positions 10$^7$ years ago in circles centered on their median position as if we were looking down on the plane of the Galaxy (i.e. we ignore the distance of the star from the Galactic plane). As before, there are 19 stars in a 50 pc sphere around Vela, while a 50 pc circle centered on their median position 10$^7$ years ago contains only 9 of them along with 22 other stars, so the completeness is 47% and the contamination is 79%. A 100 pc circle contains 16 of the stars along with 140 other stars leading to a completeness of 84% and a contamination rate of 90%. If instead we consider a 100 pc sphere, which contains 152 stars, a 100 pc circle contains 73 of them with 73 additional stars for a completeness of 58% and a contamination rate of 50%. For a 150 pc circle, the completeness and contamination increase to 76% and 63%, respectively. This age corresponds to the life time of a $\sim 20 M_\odot$ star – a $\sim 10 M_\odot$ star lives three times longer so the completeness will be far lower and the contamination will be far higher. For the 50 pc sphere, the completeness/contamination for the 50 pc and 100 pc circles are 11%/89% and 26%/90%, respectively. For the 100 pc sphere, the completeness/contamination for the 100 pc and 150 pc circles are 14%/56% and 28%/64%, respectively.

If the environment of Vela is typical, a 50 pc projected search radius includes almost none of the $\gtrsim 5 M_\odot$ stars that were within 50 pc of the progenitor at birth – the stars within this radius are overwhelmingly stars which were more distant from the progenitor at birth. A larger, 100 pc projected search radius does capture a reasonable fraction of the stars born within 100 pc of the progenitor, but they are still only about half of the stars within that projected radius. This strongly suggests that this method of analysis cannot estimate the progenitor properties for individual supernova remnants or supernovae in external galaxies – it can only statistically estimate the progenitor properties for large ensembles of targets. Even with complete three dimensional information, as we have for Vela, there are significant problems with completeness and contamination in such small regions on the 30 million year time scale before $\sim 10 M_\odot$ stars explode.

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DATA AVAILABILITY STATEMENT

All data used in this paper are publicly available.

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