The Class of $J$-Isolated Stars

Efrat Sabach$^1$ and Noam Soker$^1$

ABSTRACT

We suggest that stars whose angular momentum ($J$) does not increase by a companion, star or planet, along their post-main sequence evolution have much lower mass loss rates along their giant branches. Their classification to a separate group can bring insight on their late evolution stages. We term these $J$-isolated stars, or $J$-isolated stars. We argue that the mass loss rate of $J$-isolated stars is poorly determined because the mass loss rate expressions on the giant branches are empirically based mainly on stars that experience strong binary interaction, with stellar or sub-stellar companions, e.g., planetary nebula (PN) progenitors. We postulate that the average mass loss rate of $J$-isolated stars during their giant phases is much lower than of non-$J$-isolated stars. We explore some aspects of this assumption and find that such stars with an initial mass $M_i \simeq 1 - 2M_\odot$ reach higher luminosities and radii on the upper asymptotic giant branch (AGB), and hence are more likely to swallow brown dwarfs and planets during the AGB than traditional calculations predict. This might lead to the formation of elliptical PNe and account for bright PNe in old stellar populations. We also find that under our assumption the Sun, a $J$-isolated star, will most likely swallow the Earth during the AGB phase.

1. INTRODUCTION

Detailed observations over the years have strengthened the notion that the mass loss process of evolved stars is highly variable. Examples include the huge mass loss rate of luminous blue variable (LBV) stars that experience major eruptions, such as $\eta$ Carinae (e.g., Smith & Owocki 2006), pre-outbursts of some core collapse supernovae (CCSNe; e.g., Mauerhan et al. 2014; Graham et al. 2014; Svirski & Nakar 2014; Tartaglia et al. 2016; Ofek et al. 2016), and the dense shells and lobes of many planetary nebulae (PNe), as evidence from hundreds of images (e.g., Balick 1987; Chu et al. 1987; Corradi & Schwarz 1995; Manchado et al. 1996; Sahai & Trauger 1998; Parker et al. 2016). To those we can add the three-rings around the progenitor of SN 1987A (Burrows et al. 1993), and similar blue stars such as SBW1 (Smith et al. 2013), as well as progenitor of stripped CCSNe, such as SN Ib (e.g., Kangas et al. 2017).

An interacting stellar companion can deposit energy and angular momentum to the primary mass-losing star. Interaction with stellar companions outside the envelope of the primary star, mainly by tidal spin-up, suggests that in many cases angular momentum is more significant than energy. Evolved red giant branch (RGB) and asymptotic giant branch (AGB) stars can acquire a large amount of angular momentum by swallowing planets (e.g., Soker 1996; Carlberg et al. 2004; Villaver & Livio 2004; Mustill & Villaver 2012; Nordhaus & Spiegel 2013; García-Segura et al. 2014; Staff et al. 2013; Aguilera-Gómez et al. 2016). In those cases deposition of angular momentum is more significant than deposition of energy, e.g., for the operation of a dynamo in the envelope of the giant star (e.g., Nordhaus & Blackman 2006). Stars whose angular momentum

---

$^1$Department of Physics, Technion – Israel Institute of Technology, Haifa 32000, Israel; efrats@physics.technion.ac.il; soker@physics.technion.ac.il
$J$ does not increase in their post-main sequence evolution experience a different mass loss history than those that suffer interaction with stars, brown dwarfs, and planets.

A star that along its entire evolution does not acquire angular momentum from a stellar companion or a sub-stellar companion, or that the angular momentum it acquires $J_{\text{dep}}$ is less than fraction $\beta_J$ of the maximum value it can have on the main sequence $J_{\text{MS, max}}$, is termed a 

$$J_{\text{dep}} \leq \beta_J J_{\text{MS, max}}$$

for a Jisolated star. (1)

At this point there is no accurate theory for mass loss rate of red giant stars, and we cannot determine the exact value of $\beta_J$. In this preliminary study of the properties of Jisolated stars, we take a crude estimate of $\beta_J \approx 0.1 - 1$. In any case, the exact value of $\beta_J$ has no real influence on the conclusions reached in this study.

A large fraction of stars with zero-age main sequence (ZAMS) mass of $M_{\text{ZAMS}} > 1M_\odot$ are in close binary systems, or harbour planetary systems (e.g., Bowler et al. 2010). These are sufficient to account for observed PNe (De Marco & Soker 2011), as it seems that most PNe result from binary interaction (De Marco & Moe 2005; Soker & Subag 2005; Moe & De Marco 2006). Namely, Jisolated stars form no PNe, or at most they form spherical and very faint PNe (also termed hidden PNe). When massive stars are considered, the fraction of stars that will experience post-main sequence interaction increases (e.g., Moe & Di Stefano 2015). This implies that the fraction of Jisolated stars steeply decreases with increasing initial stellar mass.

The above considerations and the list of evolved stars that result from binary interaction suggest that as much as our understanding of the mass loss process from evolved interacting stars in binary (and triple) systems is poor, our knowledge of the mass loss rate from Jisolated stars is poorer.

We here propose that the mass loss rate observed in evolved stars, such as progenitors of PNe, is a result of a binary interaction. Namely, the fitting formulae of mass loss rates from RGB and AGB stars are actually applicable to stars that experienced binary interaction, with stellar or sub-stellar objects, during their post-main sequence evolution (non-Jisolated stars). We further propose that the mass loss rate on the RGB and AGB of Jisolated stars is much lower than what these fitting formulae give. In section 2 we compare several properties of stars that evolve to the end of the AGB under the assumption of low mass loss rate, with those of stars that evolve according to the commonly used mass loss rate. In section 3 we summarize the results and discuss the implications of our treatment of Jisolated stars, mainly regarding the interaction of planets and evolved stars on the AGB, and PN formation. We postpone the discussion on the luminosity function of PNe to a future study.

## 2. REDUCED MASS LOSS RATE

To study some effects of mass loss we conduct stellar evolution simulations using the Modules for Experiments in Stellar Astrophysics (MESA), version 9575 (Paxton et al. 2011). We calculate stellar evolution from ZAMS until the formation of a white dwarf (WD) for four stars in the mass range of $1 - 2M_\odot$ with solar metallicity, $Z = 0.02$, while varying the mass loss rate. We point out that as there is an ongoing debate as to the exact value of the solar metallicity, e.g., Vagnozzi (2013), we also ran our simulations for a lower metallicity of $Z = 0.014$. As we derived similar results and conclusions we do not present the calculations for $Z = 0.14$ in detail.
The empirical mass loss formula for red giant stars of Reimers (1975) is commonly expressed as
\[
\dot{M} = \eta \times 4 \times 10^{-13} L M^{-1} R,
\]
where \( M \), \( L \) and \( R \) are in solar units and have their usual meaning, and \( \eta \) is the scaling parameter for the mass loss rate efficiency set by observational constraints. Here we do not go into the mass loss prescription or mechanism as this is a topic of much review (e.g., Lafon & Berruyer 1991 and Schröder & Cuntz 2005). We only study the effects of mass loss reduction on the evolution of isolated stars under the assumption that they experience a much lower mass loss rate than non-isolated stars.

We study stellar models with four initial masses, and for each compare the evolution with the commonly used mass loss to the evolution with reduced mass loss. The typical value of the Reimers parameter for solar type stars is \( \sim 0.5 \) (Guo et al. 2017). Here we treat the "typical" solar type evolution and mass loss to be as taken in MESA, where the Reimers mass loss prescription is taken for the RGB and the prescription of Bloecker (Bloecker 1995) is taken for the AGB. The commonly used mass loss efficiency parameter for solar type stars in MESA is taken to be \( \eta = 0.7 \) both on the RGB and AGB. Accordingly we compare the evolution with a mass loss parameter of \( \eta = 0.7 \) to the case of a much lower mass loss rate of \( \eta = 0.07 \), both for the RGB and the AGB. The notion of a much lower mass loss-rate is not new. Miglio et al. (2012), for example, find that for the old metal-rich cluster NGC 6791 the red giant mass loss rate should have a parameter of \( \eta = 0.1 \). We differ in that we conduct a systematic comparison, and attribute the low mass loss rate to isolated stars. Some of the simulated cases are listed in Table 1.

| Simulated models | \( M_{i} \) | \( Z \) | \( \eta \) | \( R_{\text{TRGB}} \) | \( R_{\text{TAGB}} \) | \( L_{\text{PHF}} \) | \( M_{\text{f} \text{PHF}} \) | \( M_{f} \) | \( \xi_{R} \) | \( \xi_{L} \) |
|------------------|-------------|--------|--------|-----------------|--------------|--------------|-----------------|-------------|----------|----------|
| \( M_{\odot} \) | \[M_{\odot}\] | | | \[R_{\odot}\] | \[R_{\odot}\] | \[L_{\odot}\] | \[M_{\odot}\] | \[M_{\odot}\] | \[\text{R} \] | \[\text{L} \] |
| 1 \( = 1 M_{\odot} \) | 0.02 | 0.7 | 141 | 120 | 1.6 \( \times 10^{3} \) | - | 0.52 |
| 1 \( = 1.5 M_{\odot} \) | 0.02 | 0.07 | 139 | 358 | 4.0 \( \times 10^{3} \) | 0.10 | 0.56 | 3 | 2.5 |
| 1.2 \( = 2 M_{\odot} \) | 0.02 | 0.7 | 149 | 158 | 2.2 \( \times 10^{3} \) | - | 0.54 |
| 1.5 \( = 2.5 M_{\odot} \) | 0.02 | 0.7 | 141 | 394 | 5.3 \( \times 10^{3} \) | 0.24 | 0.57 | 2.5 | 2.4 |
| 2 \( = 3 M_{\odot} \) | 0.02 | 0.7 | 130 | 286 | 3.8 \( \times 10^{3} \) | - | 0.55 |
| 2 \( = 3.5 M_{\odot} \) | 0.02 | 0.7 | 102 | 325 | 5.3 \( \times 10^{3} \) | - | 0.56 |
| 2 \( = 4 M_{\odot} \) | 0.02 | 0.07 | 87 | 563 | 8.1 \( \times 10^{3} \) | 0.54 | 0.62 | 1.7 | 1.5 |
| 1.2 \( = 1.5 M_{\odot} \) | 0.014 | 0.7 | 148 | 187 | 2.9 \( \times 10^{3} \) | - | 0.53 |
| 1.2 \( = 1 M_{\odot} \) | 0.014 | 0.07 | 165 | 423 | 5.1 \( \times 10^{3} \) | 0.25 | 0.57 | 2.3 | 1.8 |

Table 1: parameters listed are the initial mass, metallicity, mass loss efficiency coefficient according to the Reimers mass loss equation (eq.2), radius at the tip of the RGB, radius at the tip of the AGB, luminosity and envelope mass prior to the last He flash (PHF), and final mass of remnant. The luminosity varies non-monotonically along the AGB, so the value of \( L_{\text{PHF}} \) is an approximate value. We also define the ratios of maximum AGB radius and pre He flash luminosities, between the isolated to non-isolated stars for each initial mass, \( \xi_{R} = \frac{R_{\text{TAGB}(0.07)}}{R_{\text{TAGB}(0.7)}} \) and \( \xi_{L} = \frac{L_{\text{PHF}(0.07)}}{L_{\text{PHF}(0.7)}} \), respectively, and list them in the last two columns.

In Fig. 1 we present the evolution of stars with initial masses of \( M_{i} = 1 M_{\odot}, 1.5 M_{\odot}, \) and \( 2 M_{\odot}, \) both for the case of the commonly used mass loss rate, \( \eta = 0.7 \) (solid lines), and for a ten fold reduced mass loss rate, i.e., \( \eta = 0.07 \) (dashed lines). The left panels show the radius of the star from the MS until the formation of a WD. The right panels show the radius and mass during the last \( 10^{5} \) yr of the final AGB phase.
From Fig. 1 and the properties we list in Table 1 we conclude the following. (1) The reduced mass loss rate we assume here for Jsolated stars brings the radius on the AGB to be much larger, by a factor of about 1.7 for the $M_i = 2M_\odot$ case, and up to a factor of about 3 for the $M_i = 1M_\odot$ case, in comparison with non-Jsolated stars (commonly used mass loss rate). Most significant is that the AGB radius of Jsolated stars is much larger than their radius on the tip of the RGB. (2) The luminosities prior to the He shell flashes on the AGB are much larger (by a factor of up to 2.5) in cases with reduced mass loss rate. (3) The final mass of the star, the bare AGB core, is larger for the reduced mass loss rate cases, implying much larger post-AGB luminosities.

In Fig. 2 we present the evolution of a star with an initial mass of $M_i = 1.2M_\odot$ similar to Fig. 1. For this case we also present the luminosity of the star during the last $10^5$yr of the AGB phase (lower right panel). One implication of the Jsolated evolution is presented in the lower left panel. We present for the $\eta = 0.07$ case the ratio of the stellar radius to the orbital separation of a planet that has an initial (ZAMS) orbital separation of $a_i = 3$ AU. We calculate the planet’s orbital separation under the influence of the stellar mass loss alone, ignoring tidal interaction. As the ratio on the tip of the AGB becomes $R_{\text{max}}/a \approx 0.5$, we expect that tidal interaction will bring a planet of mass $m_p \gtrsim M_{\text{Jupiter}}$ into the envelope at the tip of the AGB (Soker [1996]). An elliptical PNe might be formed. Non-Jsolated stars of mass $M_i = 1.2M_\odot$ and with $\eta = 0.7$, will not engulf such a planet, and will form a spherical and very faint PN (e.g., Soker & Subag 2005; De Marco & Moe 2005; Moe & De Marco 2006; De Marco 2009).

3. DISCUSSION AND SUMMARY

The average mass loss rate that is observationally derived for giant stars includes many stars that experience interaction with stellar and sub-stellar companions. The processes that take place during the interaction, from tidal spin-up to a full merger in a common envelope evolution, substantially increase the mass loss rate. In the present study we classified evolved stars that do not acquire much angular momentum, as expressed in eq. (1), into a class that we term Jsolated stars. We suggested that the average mass loss rate of Jsolated stars is much lower than that of interacting stars.

We simulated the evolution of four stellar models from their ZAMS to the WD phase with the commonly used mass loss rate, and compared their evolution with a mass loss rate that is lower by a factor of ten. The later value is chosen to simulate our suggested evolution of Jsolated stars. We presented the results in figures and and in Table 1. The main results are that low mass Jsolated stars reach much larger radii on their upper AGB and much higher luminosities on their upper AGB and post-AGB phases than non-Jsolated stars do.

Our assumption, if holds, and the classification to Jsolated stars have some very interesting implications.

The fate of the Earth. In the commonly used mass loss rate, the fate of the Earth mostly depends on the strength of the tidal interaction between Earth and the giant Sun. Due to the large sensitivity to tidal interaction (and even to external planets; see Veras 2016), different studies have reached different conclusions on the question of whether the Sun will swallow the Earth, maybe already during its RGB peak (Schröder & Connon Smith 2008), or whether the Earth will marginally survive engulfment (e.g., Rybicki & Denis 2001). We note that the Sun is a Jsolated star. Or, in case it will swallow Jupiter, it will become a non-Jsolated star only during the later stages of its AGB phase. Whether the Sun will swallow Jupiter or not depends strongly on the poorly known strength of the tidal interaction. In Fig. 3 we present the ratio of the radius of a solar model to the orbital separation of Earth. Clearly, our assumption of a much
lower mass loss rate of Jisolated stars implies that Earth will be swallowed by the Sun and will be evaporated in the giant envelope of the Sun, about 7 billion years from present day. This conclusion does not depend on the tidal interaction strength.

The fraction of planetary nebulae (PNe) that are shaped by planets. A non negligible fraction of PNe are predicted to be shaped by brown dwarfs and planets (e.g., Soker 1996 and De Marco & Soker 2011). The much larger radii that Jisolated stars reach on the AGB increases their chance to interact with very low mass MS stars and with sub-stellar objects, hence leading to a non-spherical PN. Strictly speaking, these are actually non-Jisolated stars, as at the end they do acquire a large amount of angular momentum by swallowing the sub-stellar object. In any case, our results increase the expected number of PNe that are shaped by sub-stellar objects.

The PN luminosity function. One of the greatest puzzles of low-mass stellar evolution is the finding that the \([\text{O III}] \lambda 5007\) bright-end cutoff of the PN luminosity function (PNLF) is insensitive to the age or metallicity of the stellar population (e.g., Ciardullo 2010). Our results might hint to a solution to this puzzle of bright PNe that are formed by \(M_i \approx 1 - 1.3 M_\odot\) stars. The commonly used mass loss rate in the above mass range leads to relatively faint post-AGB stars, that cannot power the brightest PNe. However, if the Jisolated mass loss rate is indeed low, then as we have shown these stars reach much higher luminosities and radii on the upper AGB. The much larger radii implies that Jisolated stars can swallow a low mass MS star, or a brown dwarf, or a massive planet, on the upper AGB (again, if they do so, they become non-Jisolated stars). This interaction leads to the ejection of a dense nebula of a mass of \(\approx 0.2 M_\odot\). The much brighter core then powers the bright \([\text{O III}] \lambda 5007\) emission. We note that in a new set of calculations Miller Bertolami (2016) find that the post-AGB luminosity values are higher than in previous older calculations. We raise the possibility that these new calculations together with our assumption of a very low mass loss rate of Jisolated stars with late engulfment of a very low mass companion, can account for the brightest PNe in old stellar populations.

The initial-final mass relation. The much lower mass loss rate of Jisolated stars does not change much the initial-final mass relation (Kalirai et al. 2008). First, the fraction of Jisolated stars is small, as most stars are expected to interact with stellar or sub-stellar companions. Second, Jisolated stars will account for the more massive WD masses that are found for each initial mass, e.g., possibly as polluted WDs. The fraction of Jisolated stars, a new estimate of the number of PNe shaped by sub-stellar objects, and a detailed study of the PNLF will be the topics of a forthcoming paper.

The masses of polluted WDs. In a preliminary study, Felipe Maldonado Sanchezin (2017) finds that polluted WDs within 200 pc from the Sun have an average and median masses of 0.66\(M_\odot\) and 0.65\(M_\odot\), respectively, compared with 0.64\(M_\odot\) and 0.59\(M_\odot\) for non polluted WDs. If the polluted WDs results hold we propose the following explanation for this preliminary finding. Polluted WDs acquire their metals from small bodies originating in debris disks (e.g., Farihi 2016 for a recent review). Most likely the debris disk could survive until the WD phase because there was no close stellar companion. Namely, we argue that a large fraction of polluted WDs result from Jisolated stars. As we found in this paper, Jisolated stars reach higher final masses, e.g., the masses of the descendant WDs, than non-Jisolated stars. We speculate that this accounts for the finding by Felipe Maldonado Sanchezin (2017) that polluted WDs are more massive on average than non-polluted WDs.

This research was supported by the Israel Science Foundation and by the E. and J. Bishop Research Fund at the Technion.
REFERENCES

Aguilera-Gómez, C., Chanamé, J., Pinsonneault, M. H., & Carlberg, J. K. 2016, ApJ, 829, 127
Balick, B. 1987, AJ, 94, 671
Bowler, B. P., Johnson, J. A., Marcy, G. W., et al. 2010, ApJ, 709, 396
Bloecher, T. 1995, A&A, 297, 727
Burrows, C. J., Krist, J., Hester, J. J., et al. 1995, ApJ, 452, 680
Carlberg, J. K., Majewski, S. R., & Arras, P. 2009, ApJ, 700, 832
Chu, Y.-H., Jacoby, G. H., & Arendt, R. 1987, ApJS, 64, 529
Ciardullo, R. 2010, PASA, 27, 149
Corradi, R. L. M., & Schwarz, H. E. 1995, A&A, 293, 871
De Marco, O., & Moe, M. 2005, Planetary Nebulae as Astronomical Tools, 804, 169
De Marco, O. 2009, PASP, 121, 316
De Marco, O., & Soker, N. 2011, PASP, 123, 402
Farihi, J. 2016, New A Rev., 71, 9
Felipe Maldonado Sanchezin, R. 2017, in Planetary systems Beyond the Main Sequence II, [http://planets-beyond-ms.weebly.com/presentations.html]
García-Segura, G., Villaver, E., Langer, N., Yoon, S.-C., & Manchado, A. 2014, ApJ, 783, 74
Graham, M. L., Sand, D. J., Valenti, S., et al. 2014, ApJ, 787, 163
Guo, J., Lin, L., Bai, C., & Liu, J. 2017, Ap&SS, 362, #15
Kalirai, J. S., Hansen, B. M. S., Kelson, D. D., et al. 2008, ApJ, 676, 594-609
Kangas, T., Portinari, L., Mattila, S., et al. 2017, A&A, 597, A92
Lafon, J.-P. J., & Berruyer, N. 1991, A&A Rev., 2, 249
Manchado, A., Guerrero, M. A., Stanghellini, L., & Serra-Ricart, M. 1996, The IAC morphological catalog of northern Galactic planetary nebulae, Publisher: La Laguna, Spain: Instituto de Astrofisica de Canarias (IAC), 1996, Foreword by Stuart R. Pottasch, ISBN: 8492180609,
Mauerhan, J., Williams, G. G., Smith, N., et al. 2014, MNRAS, 442, 1166
Miglio, A., Brogaard, K., Stello, D., et al. 2012, MNRAS, 419, 2077
Miller Bertolami, M. M. 2016, A&A, 588, A25
Moe, M., & De Marco, O. 2006, ApJ, 650, 916
Moe, M., & Di Stefano, R. 2015, ApJ, 801, 113
Mustill, A. J., & Villaver, E. 2012, ApJ, 761, 121
Nordhaus, J., & Blackman, E. G. 2006, MNRAS, 370, 2004
Nordhaus, J., & Spiegel, D. S. 2013, MNRAS, 432, 500
Ofek, E. O., Cenko, S. B., Shaviv, N. J., et al. 2016, ApJ, 824, 6
Parker, Q. A, Bojicic, I., & Frew, D. J 2016, arXiv:1603.07042
Paxton, B., Bildsten, L., Dotter, A., et al. 2011, ApJS, 192, 3
Reimers, D. 1975, Memoires of the Societe Royale des Sciences de Liege, 8, 369
Rybicki, K. R., & Denis, C. 2001, Icarus, 151, 130
Sahai, R., & Trauger, J. T. 1998, AJ, 116, 1357
Schröder, K.-P., & Connon Smith, R. 2008, MNRAS, 386, 155
Schröder, K.-P., & Cuntz, M. 2005, ApJ, 630, L73
Smith, N., Arnett, W. D., Bally, J., Ginsburg, A., & Filippenko, A. V. 2013, MNRAS, 429, 1324
Smith, N., & Owocki, S. P. 2006, ApJ, 645, L45
Soker, N. 1996, ApJ, 460, L53
Soker, N., & Subagh, E. 2005, AJ, 130, 2717
Staff, J. E., De Marco, O., Wood, P., Galaviz, P., & Passy, J.-C. 2016, MNRAS, 458, 832
Svirski, G., & Nakar, E. 2014, ApJ, 788, L14
Tartaglia, L., Pastorello, A., Sullivan, M., et al. 2016, MNRAS, 459, 1039
Vagnozzi, S. 2017, arXiv:1703.10834
Veras, D. 2016, MNRAS, 463, 2958
Villaver, E., & Livio, M. 2009, ApJ, 705, L81

This preprint was prepared with the AAS \LaTeX\ macros v5.2.
Fig. 1.— Evolution of three stellar models of initial masses $M_i = 1M_\odot$, 1.5$M_\odot$, and 2$M_\odot$, calculated with MESA until the formation of a WD for a star with the commonly used mass loss rate, $\eta = 0.7$ (solid lines), and for a ten fold reduced mass loss rate, $\eta = 0.07$ (dashed lines). Left panels: The radius of the star during the evolution from the MS phase until the final WD stage for the commonly used mass loss rate (red), and a reduced mass loss rate (black). Right panels: The radius (left axes), and the mass (right axes, thick lines) for $\eta = 0.7$ (blue) and $\eta = 0.07$ (magenta), during the final 10$^5$yr of the AGB phase.
Fig. 2.— Similar to Fig. 1 but for the case of $M_i = 1.2 M_\odot$. Two additional graphs are presented. In the lower left panel we present the ratio of the stellar radius to the orbital separation of a planet at an initial orbital separation of $a_i = 3$ AU for the $\eta = 0.07$ case. In the lower right panel we present the luminosity of the star during the last $10^5$ yr of the AGB phase, for $\eta = 0.7$ (purple) and $\eta = 0.07$ (orange).
Fig. 3.— The ratio of the evolving solar radius to the orbital separation of Earth under the assumption of a very low mass loss rate of Isolated stars. As an Isolated star, we find that under our assumptions the Sun will swallow the Earth, insensitive to the tidal interaction strength.