Efficient common-envelope ejection through dust-driven winds

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ABSTRACT

Common-envelope evolution (CEE) is the short-lived phase in the life of an interacting binary system during which two stars orbit inside a single shared envelope. Such evolution is thought to lead to the inspiral of the binary, the ejection of the extended envelope, and the formation of a remnant short-period binary. However, detailed hydrodynamical models of CEE encounter major difficulties. They show that following the inspiral most of the envelope is not ejected; though it expands to larger separations, it remains bound to the binary. Here we propose that dust-driven winds can be produced following the CEE. These can evaporate the envelope following similar processes operating in the ejection of the envelopes of AGB (Asymptotic Giant Branch) stars. Pulsations in an AGB star drive the expansion of its envelope, allowing the material to cool down to low temperatures thus enabling dust condensation. Radiation pressure on the dust accelerates it, and through its coupling to the gas it drives winds that eventually completely erode the envelope. We show that the inspiral phase in CE binaries can effectively replace the role of stellar pulsation and drive the CE expansion to scales comparable with those of AGB stars, and gives rise to efficient mass-loss through dust-driven winds.

Key words: stars: AGB and post-AGB – (stars:) binaries (including multiple): close – stars: mass-loss – stars: winds, outflows.

1 INTRODUCTION

Post-common-envelope binaries are thought to give rise to many types of interacting binary systems. These include the progenitors of transient explosive events such as Type Ia supernovae, short gamma-ray bursts, X-ray binaries, and double WD/NS/BH systems inspiraling through GW emission. However the evolved components of such systems must have once been orders-of-magnitude larger than would fit within the size of the observed present-day systems. The observations of such systems therefore require some migration process to drive these binaries to their current compact configuration.

Common-Envelope Evolution (CEE) is the short-lived phase in the life of an interacting binary star during which two stars orbit inside a single, shared envelope. The interaction of the stellar components with the envelope through gravitational torques leads to their inspiral into a short-period orbit, and is thought to also lead to the ejection of the CE. CEE is therefore currently accepted as the evolutionary process allowing the formation of compact short-period binaries (see Podsiałowski 2001; Izzard et al. 2012; Ivanova et al. 2013; Soker et al. 2013; Soker 2017 for reviews). However, detailed hydrodynamical models of CEE encounter major difficulties; they show that following the inspiral phase most of the envelope is not ejected, but only expands to larger separations where it still remains bound to the binary (e.g. Ricker & Taam 2012; Ivanova et al. 2013; Ivanova, Justham & Podsiałowski 2015; Kuruwita, Staff & De Marco 2016; Ohlmann et al. 2016; Iaconi et al. 2017).

It was suggested (Nandez, Ivanova & Lombardi 2015; Clayton et al. 2017, and references therein) that recombination energy stored in ionized hydrogen and helium may provide an additional energy source driving envelope ejection. Such a scenario follows similar models suggested in the past for the ejection of the envelope of single asymptotic giant-branch (AGB) stars (e.g. Roxburgh 1967; Paczyński & Ziolkowski 1968; Han, Podsiałowski & Eggleton 1994). In this context, the fraction of the recombination energy lost to radiation is still debated and is actively studied (Soker & Harpaz 2003; Ivanova 2011; Clayton et al. 2017; Sabach et al. 2017). It is also still not clear whether this channel can eject the CE in all cases (Clayton et al. 2017), and whether it can explain wide post-CE orbits (Ivanova et al. 2015). Irrespective of this channel, one can follow a different path in searching for mechanisms that eject the envelope in single AGB stars, and extend them to CEE. In this channel, we propose to follow the current paradigm for the ejection of the envelope of an AGB star, namely dust-driven winds (see Lamers & Cassinelli 1999, for a review), and apply it for CEE scenarios.

Mass-loss in AGB stars is thought to proceed through slow stellar winds. Stellar pulsations levitate material outwards sufficiently far to allow its cooling to low temperatures at which dust condensation becomes possible. The dust grains are accelerated away due to radiation pressure from the star, and through their collisional cou-
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2 DUST-DRIVEN WINDS

The current paradigm for the mass-loss in AGB stars and luminous red super-giants is through dust-driven winds (see Lamers & Cassinelli 1999, for a review). As these stars evolve they experience significant pulsations that levitate material far beyond the stellar surface, where it can cool and condense into dust grains. The grains absorb and scatter stellar photons from the star, and are accelerated outwards. Collisional coupling of the dust grains and the surrounding gas results in an effective radiation pressure, mediated by dust, on the stellar envelope. Given the large opacity of the dust grains, the evolved star effectively becomes super-Eddington, and the gaseous envelope, accelerated beyond the escape velocity of the star, becomes unbound and is ejected through a slow wind (with velocities comparable to the escape velocity from the star).

Following Lamers & Cassinelli (1999) one can define, $\Gamma_d$, the ratio of radiative acceleration to gravity. In case of radiation forces on dust, this ratio is $\Gamma_d = k_{dp}\lambda_{\text{d}}/4\pi GM_\star$, where $k_{dp}$ is the radiation pressure mean opacity, and $L_\star$ and $M_\star$ are the luminosity and mass of the star, respectively. Winds can occur if $\Gamma_d$ increases outwards and becomes greater than unity, beyond some radius. The limiting luminosity for such dust-driven winds can then be derived by taking $\Gamma_d$ to unity to obtain

$$L_\star > \frac{4\pi c G M_\star}{k_{dp}} \approx 400 L_\odot \frac{M_\star/M_\odot}{k_{dp}/30 \text{cm}^2\text{g}^{-1}}$$

(1)

for mean opacity $k_{dp}$, derived from detailed calculations over many types of grains. The survival of a test grain can then be determined by deriving its radiative equilibrium temperature. If the dust temperature exceeds the condensation temperature, the grain will sublimate rather than grow. In addition, the density should be sufficiently high to allow accumulation of solids contribution to the dust growth. Effectively these conditions require low-temperature, but high-density environments, which can be attained in the envelope of pulsating AGB star. As we discuss in the following section, similar conditions also exist in CE binaries.

The distance from the star at which dust-grain temperature is below the condensation temperature is independent of the density of the ambient gas. As explained in details in Lamers & Cassinelli (1999), the low-equilibrium temperature is achieved when the condensation radius, represented by $R_C$ has the following relation with the condensation temperature, $T_C$:

$$W(R_C) = \left(\frac{T_C}{T_\star}\right)^{p+4}$$

(2)

where the opacity is assumed to follow a power-law dependence $\kappa \propto \lambda^{-p}$ (where the specific relation depends on the grains properties such as composition and size distribution), and $R_\star, T_\star$ are the stellar radius and temperature, respectively. $W(r)$ is the ‘geometrical dilution factor’ and depends on the optical depth at the radius. In most cases of AGBs, the optical depth of the gas in the region of the condensation radius is much lower than unity (the intensity incident on the dust grains is direct star light) and thus $W(R_C) \approx (R_\star/3R_C)^2$, and as a consequence:

$$R_C \approx \left(\frac{R_\star}{2}\right) \left(\frac{T_C}{T_\star}\right)^{-\frac{p+4}{2}}$$

(3)

The condensation radius is typically ~2–3 times the stellar radius of the evolved star (Höfner 2008). While the temperature and radiation field determine whether grains can form and at a given distance from the star, it is the density at the dust formation radius that determines the mass-loss rate of the wind. The density determines whether there is sufficient momentum coupling between grains and the gas. Efficient mass-loss can be maintained as long the atmospheric-density scaleheight can be significantly increased relative to that of gas-pressure-supported hydrostatic atmospheres. A critical point is attained when the gas velocity exceeds the sound speed, and enhanced density can be developed through shocks. This may occur just before $\Gamma_d$ becomes larger than unity. Once the grains
form, they are accelerated through radiation pressure, and through their strong coupling to the gas, these grains accelerate the gas up to supersonic velocities. The gas density then drops rapidly with the radius and further dust growth is inhibited. This feedback provides a mechanism for conservation of the grain sizes, and their effectiveness in inducing mass-loss. In case of a thick shell, \( \Gamma_d \) will be larger than 1 throughout the region, where the temperature decreases between the condensation temperature and \( T_{\text{rad}} \) where \( \Gamma_d = 1 \).

3 DUST-ASSISTED COMMON-ENVELOPE EJECTION

During the CE phase of an RG binary, the companion spirals inside the envelope due to gravitational torques, transferring angular momentum and energy to the envelope of the evolved star, which leads to a substantial expansion of the envelope. Later, the inspiral slows down, leaving behind a bloated star containing the remnant core of the RG, which radiates on the now extended gaseous envelope. This process transforms the conditions in the RG envelope to be far more similar to those existing in pulsating AGB stars, and thereby allows for similar production of dust-driven winds.

Although the original temperature profile of the RG is too high for dust formation, the CE expands significantly during the CE phase, and thus far from the core it is sufficiently cool but still dense enough to allow dust condensation. Indeed, previous theoretical studies suggested the formation of dust in the ejecta of CEs (Lü, Zhu & Podsiadlowski 2013). These, however, explored dust formation after the ejection of the envelope in the unbound material, while our focus is on the initially bound material following its expansion due to the inspiral. The conditions in the latter case differ from those in the ejected material. We also note that direct observations show the existence of a significant amount of dust shrouding/obscuring post-CE/merger objects (Kamiński, Schmidt & Tytenda 2010; Kamiński & Tytenda 2011; Tylenda et al. 2011; Barsukova et al. 2014; Tytenda et al. 2015). The radiation from the inner parts of the star applies radiation pressure on the dust, accelerating it above the sound speed of the gas, and the collisional coupling of the dust to the gas can eventually result in the ejection of the entire outer layer of the envelope. Without the existence of the dust the extended envelope would eventually cool down, release the energy as radiation, and then fall back. Let us now consider this in more detail.

3.1 The dust condensation radius

The luminosity of the RG stellar core is conserved during the CE phase, and its source is the nuclear reactions in the star’s core, which do not change during the process. The luminosity of the RG companion (an MS- Main Sequence or a compact object) can typically be neglected compared with that of the RG core; hence we make a simplified assumption that the total luminosity in some given layer of the extended envelope is comparable to the core luminosity. If we consider the inner part of the star below the condensation radius as a blackbody (the optical depth is large) we can estimate the effective temperature at the condensation radius, by using the initial values (prior to the CE) of the luminosity \( L_i \), the radius \( R_i \), and the effective temperature \( T_i \) of the RG star at this radius:

\[
\frac{L}{L_i} = \frac{4\pi \sigma R_i^4 T_i^4}{4\pi \sigma r^2 T(r)^4} \rightarrow T(r) = \sqrt{\frac{R_i}{r}} T_i
\]

Together with equation (2) (with \( p \approx 1 \) and the optically thick approximation \( \kappa R_i \approx 1/2 \), the condensation radius can be calculated as follows:

\[
R_C = 0.52^{1/5} \left( \frac{T_C}{T_i} \right)^{-2} R_i
\]

Usually the condensation radius of an AGB is located outside the stellar surface, thus the pulsations play an important role in the gas ejection process. The pulsations determine the rate at which gas from the star reaches the condensation radius before being pushed away, and thereby determine the dust creation rate. In the post-CE case, the inspiral and possibly recombination effects may also give rise to pulsation-like behaviour (e.g. Clayton et al. 2017), but irrespective, the resulting extended envelope is already far from the RG core, and it is sufficiently cool and dense to allow dust condensation. Indeed, the initial effective temperature, \( T_i \), is comparable to that of an AGB star, consequently, equation (5) prescribes the condensation radius to initial-radius ratio \( R_C^{\text{CE}} / R_i \) to be comparable to the ratio of the condensation radius to star radius of an AGB star \( (R_{\text{AGB}} / R_i) \). Since the radius at which the bulk mass of the CE mass resides could be comparable to the radius of an AGB (e.g. Passy et al. 2012; Ricker & Taam 2012; Ivanova et al. 2013 see Fig. 1), the CE condensation radius is effectively located inside its envelope. Moreover, the envelope mass can extend beyond the condensation radius, and hence be affected by dust-induced radiation pressure, which can eventually unbind the CE. The evaporation time is mainly derived from the amount of material that can condense into dust, the amount of energy radiated on the dust, and the amount of material the dust can push outwards.

We note that convection may also play a role on time-scales longer than the CE inspiral time-scale, as in the case explored by Clayton et al. (2017), and may further drive mass from the inner regions outwards beyond the condensation radius. Indeed, Clayton et al. (2017) detailed evolution model shows the existence of non-negligible amount of envelope mass at sufficiently low temperatures to potentially allow dust condensation. In the next section, we will verify this assumption on the cases of Clayton et al. (2017) and Passy et al. (2012). It would be interesting to combine recombination models with the dust-driven models, but this is beyond the scope of the current paper.

3.2 A worked-out example

Let us consider a Sun-like star that evolved to become an RG with a radius of \( 83 R_\odot \); such a giant has an effective temperature of \( \sim 3480 \, K \), luminosity \( L \sim 1000 \, L_\odot \), and a hydrogen-exhausted core of \( \sim 0.39 \, M_\odot \), with a radius of \( \sim 0.02 \, R_\odot \). Following Passy et al. (2012) we consider the interaction of the RG with an MS companion leading to a CE phase, resulting in short-period stable orbit of the companion around the RG core, and an extended gas envelope above it.

In order to obtain the specific parameters of the post-CE RG, and in particular the density and sound speed at the condensation radius, we have repeated the simulation of Passy et al. (2012), using the MESA code for following the stellar evolution of the RG until \( \sim 340 \) K, luminosity \( L \sim 1000 \, L_\odot \), and a hydrogen-exhausted core of \( \sim 0.39 \, M_\odot \), with a radius of \( \sim 0.02 \, R_\odot \). Following Passy et al. (2012) we consider the interaction of the RG with an MS companion leading to a CE phase, resulting in short-period stable orbit of the companion around the RG core, and an extended gas envelope above it.

In order to obtain the specific parameters of the post-CE RG, and in particular the density and sound speed at the condensation radius, we have repeated the simulation of Passy et al. (2012), using the MESA code for following the stellar evolution of the RG until the post-CE core of AGB winds, showing their respective calculated dust condensation radii. Following the previous sections, the post-CE RG in this case will have a condensation radius of \( R_C \approx 340 \, R_\odot \). The total mass outside this radius is \( M_{\text{env}} \sim 0.4 \, M_\odot \), which consists of almost the entire mass in the
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Figure 1. A comparison between an evolved AGB star and a post-CE red giant remnant. Top left: An AGB star evolved from a Sun-like star of ~240\(R_\odot\) [using MESA (Paxton et al. 2011)], for which dust is expected to form at \(r\sim700\,R_\odot\) (white dashed circle), the pulsations in the outwards direction can place material from the star at that radius, resulting in continuous dust creation and outwards velocity to the existed grains. Top right: A post CE Red Giant star, for which dust formation is expected to form at \(r\sim340\,R_\odot\) (black dashed circle); following the inspiral of the companion [modelled using GADGET2 (Springel 2005)] the gaseous envelope extends even far beyond the condensation radius. Bottom: Comparison of the averaged radial density profile of the AGB and post-CE RG stars. As can be seen, the envelope of the post-CE RG extends far beyond the size of an AGB star, while retaining high densities required for dust formation.

As described in the previous section, considering the inner part of the star, below the condensation radius, as a blackbody radiation source, and taking the Rosseland opacity, \(\kappa_{\text{Ros}} = 24(77T_\odot)^{0.3}\), the temperature in a radius with optical depth \(\tau\) is \(T(\tau) = (3/4)T_\text{surf}^{4}(\tau_{\text{Ros}} + \frac{1}{3})\). The temperature therefore declines from \(T = T_\odot = 1500\) K at the condensation radius to \(T_\text{surf} \approx 880\) K, without consideration of the dust. The total optical depth, in this case is about \(\tau_{\text{tot}} \approx 10\), i.e. indeed sufficient for induction of dust-driven winds in the comparable case of an AGB was discussed by Lamers & Cassinelli (1999).

The typical time for ejection of the CE in the dust-assisted CE ejection model is determined by the rate of momentum imparted to the envelope. In order to eject the envelope one needs to accelerate the envelope up to escape velocity. Assuming a significant fraction, \(f\), of the momentum exerted by the radiation pressure on the dust is transferred to the CE, we can compare the accumulated momentum and the total momentum required to eject the envelope as

\[
t_{\text{eject}} = \frac{L_*}{c} = M_{\text{env}}v_{\text{esc}},
\]

where \(t_{\text{eject}}\) is the time to eject the envelope, \(v_{\text{esc}}\) is the escape velocity, \(L_*\) is the stellar (core) luminosity, and \(c\) is the speed of light. Taking the above values at the condensation radius we get \(t_{\text{eject}} \approx 1.3 \times 10^5(0.5/f)\) yr; comparable to the lifetime of an AGB star. Note that for the latter the mass-loss rate also depends on the rate of pulsations that bring material beyond the condensation radius. In the CE case, this amount depends on the inspiral phase, where deeper penetration of the companion likely leads to a larger extension of the CE, and hence more mass is expelled beyond the condensation radius over the inspiral time. Nevertheless, as can be seen in Clayton et al. (2017), pulsations could be produced on the longer term evolution, leading to additional expulsion of material beyond the condensation radius. For an exact calculation of the ejection time, one should perform an integration over all the values of the escape velocity \(v_{\text{esc}}\) at the region of the envelope above the condensation radius.
4 DISCUSSION AND SUMMARY

In this work, we have explored a novel scenario for CE ejection in interacting binaries. We propose that the same dust-driven wind models suggested for the ejection of AGB stellar envelopes could similarly operate in CE binaries. We show that the temperature and density conditions in CEs are comparable with those existing in the envelopes of AGB stars. In particular, most of the CE can extend beyond the dust condensation radius, following the CE inspiral phase. Hence dust could efficiently form the envelope, where it is subjected to radiation pressure. The gaseous envelope can then be accelerated outwards, forming dust-driven winds that eventually evaporate the CE.

We considered simple analytic models (similar to those previously employed for the study of AGB envelopes) to explore dust-driven CE ejection. More detailed studies using radiative-hydrodynamics modelling, as had been recently used for the study of AGB envelopes (e.g. Freytag, Liljegren & Höfner 2017, and references therein), could be similarly applied for the study of the CE case. These are beyond the scope of the current paper which provides a proof of concept for the dust-driven CE ejection scenario. These will be further explored in future studies to provide a more detailed understanding of this scenario.

We note that we have not discussed the type of the dust grains that may form in the proposed scenario. Which type of dust grains play a role in this process depends on the composition of the specific star. The mechanism of dust-driven winds in AGBs works well for C-rich stars. In O-rich stars, significant mass-loss through winds is also observed, suggesting that a similarly efficient mechanism is at work, but the dust composition may pose a challenge in this case (see Höfner 2015, for an overview). In RGs, C-enrichment can only arise from the intrinsic metallicity of the star, as dredge-up processes occurring in AGB stars do not take place in this case. However, the same solutions suggested for O-rich AGB stars such as the role played by micron-sized dust (Höfner & Andersen 2007; Höfner 2008) could similarly operate in this case. Moreover, observations suggest that dust is efficiently formed even in the merger of main-sequence stars ( Kamiński et al. 2010; Kamiński & Tylenda 2011; Tylenda et al. 2011; Barsukova et al. 2014; Tylenda et al. 2015).

In the dust-assisted CE ejection scenario, the time-scales for ejecting the envelope could be long, comparable with the lifetimes of AGB stars. In practice, CE binaries in this phase may appear very similar to AGB stars, showing dust enshrouded envelopes, and mass-loss through slow winds. Significant non-sphericity of the envelope (e.g. Ricker & Taam 2012), however, could be a distinct signature of post-CEs (possibly observed by Kamiński et al. 2010; Kamiński & Tylenda 2011; Tylenda et al. 2011; Barsukova et al. 2014; Tylenda et al. 2015). In the dust-driven CE ejection, the CE is not dynamically ejected as typically envisioned, but rather the dynamical phase introduces the conditions allowing for the long-term slow mass-loss phase. We point out that even during the dynamical phase of the inspiral, dust may form and thereby affect the appearance of the light curve and spectra of the transient CEE event and the remnant post-CE binary, and should be accounted for (see also Kamiński et al. 2010; Kamiński & Tylenda 2011; Tylenda et al. 2011; Barsukova et al. 2014; Tylenda et al. 2015; Galaviz et al. 2017, for observational evidence and theoretical discussion of the dust effects on the post-CE appearance).

Finally, though not the main focus of this paper we note that dust formation would also assist in trapping radiation arising from recombination energy, and may further assist any scenario of recombination-energy-induced CE ejection, irrespective of the dust-driven winds explored here.

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REFERENCES

Barsukova E. A., Goranskij V. P., Valeev A. F., Zharova A. V., 2014, Astrophys. Bull., 69, 67
Bowen G. H., 1988, ApJ, 329, 299
Clayton M., Podsiadlowski P., Ivanova N., Jastham S., 2017, MNRAS, 470, 1788
Freytag B., Liljegren S., Höfner S., 2017, A&A, 600, A137
Galaviz P., De Marco O., Passy J.-C., Staff J. E., Iaconi R., 2017, ApJS, 229, 36
Han Z., Podsiadlowski P., Eggleton P. P., 1994, MNRAS, 270, 121
Höfner S., 2008, A&A, 491, L1
Höfner S., 2015, in Kerschbaum F., Wing R. F., Hron J., eds, ASP Conf. Ser. Vol. 497, Why galaxies care about AGB Stars III: A Closer Look in Space and Time, Astron. Soc. Pac., San Francisco, p. 333,
Höfner S., Andersen A. C., 2007, A&A, 465, L39
Iaconi R., Reichardt T., Staff J., De Marco O., Passy J.-C., Price D., Wurster J., Herwig F., 2017, MNRAS, 464, 4028
Ivanova N., 2011, in Schmidtobreick L., Schreiber M. R., Tappert C., eds, ASP Conf. Ser. Vol. 447, Evolution of Compact Binaries, Astron. Soc. Pac., San Francisco, p. 91
Ivanova N. et al., 2013, A&A Rev., 21, 59
Ivanova N., Jastham S., Podsiadlowski P., 2015, MNRAS, 447, 2181
Izzard R. G., Hall P. D., Tauris T. M., Tout C. A., 2012, in IAU Symp. p. 95
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Kamiński T., Schmidt M., Tylenda R., 2010, A&A, 522, A75
Kamiński T., Tylenda R., 2011, A&A, 527, A75
Kuruwita R. L., Staff J., De Marco O., 2016, MNRAS, 461, 486
Lamers H. J. G. L. M., Cassinelli J. P., 1999, Introduction to Stellar Winds.
Cambridge Univ. Press, Cambridge
Liljegren S., Höfner S., Nowotny W., Eriksson K., 2016, A&A, 589, A130
Lü G., Zhu C., Podsiałowski P., 2013, ApJ, 768, 193
Nandez J. L. A., Ivanova N., Lombardi J. C., 2015, MNRAS, 450, L39
Ohlmann S. T., Röpke F. K., Pakmor R., Springel V., 2016, ApJ, 816, L9
Paczyński B., Ziolkowski J., 1968, Acta Astron., 18, 255
Passy J.-C. et al., 2012, ApJ, 744, 52
Paxton B., Bildsten L., Dotter A., Herwig F., Lesaffre P., Timmes F., 2011, ApJS, 192, 3
Podsiadlowski P., 2001, in Podsiadlowski P., Rappaport S., King A. R.,
D’Antona F., Burderi L., eds, ASP Conf. Ser. Vol. 229, Evolution of
Binary and Multiple Star Systems, Astron. Soc. Pac., San Francisco. p. 239
Podsiadlowski P., 2001, in Podsiadlowski P., Rappaport S., King A. R.,
D’Antona F., Burderi L., eds, ASP Conf. Ser. Vol. 229, Evolution of
Binary and Multiple Star Systems, Astron. Soc. Pac., San Francisco. p. 239

Ricker P. M., Taam R. E., 2012, ApJ, 746, 74
Roxburgh I. W., 1967, Nature, 215, 838
Sabach E., Hillel S., Schreier R., Soker N., 2017, MNRAS, 472, 4361
Soker N., 1992, ApJ, 386, 190
Soker N., 2004, in Dupree A. K., Benz A. O., eds, IAU Symp. Vol. 219,
Stars as Suns, Astron. Soc. Pac., San Francisco. p. 323
Soker N., 2017, MNRAS, 471, 4839
Soker N., Harpaz A., 2003, MNRAS, 343, 456
Springel V., 2005, MNRAS, 364, 1105
Tylenda R. et al., 2011, A&A, 528, A114
Tylenda R., Górny S. K., Kamiński T., Schmidt M., 2015, A&A, 578, A75
Winters J. M., Le Bertre T., Jeong K. S., Helling C., Sedlmayr E., 2000,
A&A, 361, 641

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