The impact of electron-capture supernovae on merging double neutron stars

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ABSTRACT
Natal kicks are one of the most debated issues about double neutron star (DNS) formation. Several observational and theoretical results suggest that some DNSs have formed with low natal kicks ($\lesssim 50$ km s$^{-1}$), which might be attributed to electron-capture supernovae (ECSNe). We investigate the impact of ECSNe on the formation of DNSs by means of population synthesis simulations. In particular, we assume a Maxwellian velocity distribution for the natal kick induced by ECSNe with one dimensional root-mean-square $\sigma_{\text{ECSN}} = 0.7, 1.5, 2.6, 26.5$ km s$^{-1}$. The total number of DNSs scales inversely with $\sigma_{\text{ECSN}}$ and the number of DNS mergers is higher for relatively low kicks. This effect is particularly strong if we assume low efficiency of common-envelope ejection (described by the parameter $\alpha = 1$), while it is only mild for high efficiency of common-envelope ejection ($\alpha = 5$). In most simulations (with both $\alpha = 1$ and $\alpha = 5$), more than 50 per cent of the progenitors of merging DNSs undergo at least one ECSN and the ECSN is almost always the first SN occurring in the binary system. This supports the scenario in which ECSNe are essential physical ingredients for the formation of DNSs.

Key words: methods: numerical – gravitational waves – binaries: general – stars: neutron

1 INTRODUCTION
GW170817, the first detection of a merger between two neutron stars (NSs, Abbott et al. 2017a), marked the beginning of multi-messenger astronomy. For the first time, electromagnetic emission accompanying the gravitational wave (GW) event was observed (Abbott et al. 2017b), ranging from gamma rays (e.g. Abbott et al. 2017b; Goldstein et al. 2017; Savchenko et al. 2017) to X-rays (e.g. Margutti et al. 2017), to optical, near-infrared (e.g. Soares-Santos et al. 2017; Chornock et al. 2017; Cowperthwaite et al. 2017; Nicholl et al. 2017; Pian et al. 2017) and radio wavelengths (e.g. Alexander et al. 2017).

The formation of merging double NSs (DNSs) like GW170817 is still matter of debate: understanding this process would provide crucial insights for both stellar evolution and GW astrophysics. Merging DNSs are expected to form either from the evolution of isolated close binaries (e.g. Flannery & van den Heuvel 1975; Belczynski et al. 2002; Voss & Tauris 2003; Dewi & Pols 2003; Podsiadlowski et al. 2004; Dewi et al. 2005; Tauris et al. 2017; Chruslinska et al. 2017; Kruckow et al. 2018) or through dynamical interactions in star clusters (e.g. Grindlay et al. 2006; East & Pretorius 2012; Lee et al. 2010; Ziosi et al. 2014).

Many uncertainties still affect both formation channels. In particular, one of the most debated and also one of the most important physical ingredients for the formation of DNSs is the magnitude of the natal kick imparted by the supernova (SN) explosion to the newborn NS (Janka 2012). From a study on the proper motion of 233 young isolated pulsars, Hobbs et al. (2005) estimated that their velocity distribution follows a Maxwellian curve with a one dimensional root-mean-square ($1\text{D rms}$) velocity $\sigma = 265$ km s$^{-1}$ and an average natal kick speed of $\sim 420$ km s$^{-1}$. On the other hand, there is increasing evidence that some NSs form with a significantly smaller natal kick.

Several studies (Cordes & Chernoff 1998; Arzoumanian et al. 2002; Brisken et al. 2003; Schwab et al. 2010; Verbunt et al. 2017) claim that the velocity distribution proposed by Hobbs et al. (2005) underestimates the number of pulsars with a low velocity and suggest that the natal kick distribution of NSs is better represented by a bimodal veloc-
2 Methods

MOBSE is an updated version of the BSE code (Hurley et al. 2000, 2002). Here we summarize the main characteristics of MOBSE and we describe the new features we have added to it for this work. A more detailed discussion of MOBSE can be found in Giacobbo et al. (2018) and in Mapelli et al. (2017). In this paper, we adopt the version of MOBSE described as MOBSE1 in Giacobbo et al. (2018).

The main differences between MOBSE and BSE are the treatment of stellar winds of massive stars and the prescriptions for SN explosions. Stellar winds of O and B-type stars are implemented in MOBSE as described by Vink et al. (2001), while the mass loss of Wolf-Rayet (WR) stars is implemented following Belczynski et al. (2010). Finally, the mass loss of luminous blue variable (LBV) stars is described as

$$M = 10^{-4} \tilde{J}_{\text{LBV}} \left( \frac{Z}{Z_\odot} \right)^\beta \text{M}_\odot \text{yr}^{-1}.$$  

All massive hot massive stars (O, B, WR and LBV stars) lose mass according to $M \propto Z^\beta$, where $\beta = 0.85$ if $\Gamma e < 2/3$, $\beta = 2.45 - 2.4\Gamma e$ if $2/3 \leq \Gamma e < 1$ and $\beta = 0.05$ if $\Gamma e \geq 1$ (Chen et al. 2015).

The new prescriptions for core-collapse SNe in MOBSE include the rapid and the delayed SN model described by Fryer et al. (2012) (see also Spera et al. 2015). The rapid SN model is adopted for the simulations presented in this paper, because it allows us to reproduce the remnant mass gap between $\sim 2 \text{M}_\odot$ and $\sim 5 \text{M}_\odot$ (Ozel et al. 2010; Farr et al. 2011). Pair-instability and pulsational pair-instability SNe are also implemented in MOBSE using the fitting formulas by Spera & Mapelli (2017).

Finally, we have also updated the prescriptions for core radii following Hall & Tout (2014), we have extended the mass range up to 150 M\odot (Mapelli 2016), and we have revisied the treatment of Hertzsprung-gap (HG) donors in common envelope (CE): HG donors are assumed to always merge with their companions if they enter a CE phase.

For this work, we have added several updates to the description of ECSNe and natal kicks in MOBSE, as we describe in the following sections.

2.1 Electron-capture SNe (ECSNe)

NSs can form via core-collapse SN, via ECSN or through the accretion-induced collapse of a white dwarf (WD). In MOBSE, the outcome of a core-collapse SN is considered a NS if its mass is less than 3.0 M\odot and a BH otherwise. This approach is overly simplified, but more constraints on the equation of state of a NS are required for a better choice of the transition between NS and BH.

In the case of both an ECSN and an accretion-induced WD collapse, the NS forms when the degenerate Oxygen-Neon (ONe) core collapses as a consequence of electron-capture reactions, inducing a thermonuclear runaway (Miyaji et al. 1980; Nomoto 1984, 1987; van den Heuvel 2007; Beniamini & Piran 2016).

In this paper, we use our new population-synthesis code MOBSE (Giacobbo et al. 2018), to investigate the impact of ECSNe and low natal kicks on the formation of merging DNSs.

### Table 1. Definition of the ten simulation sets.

| ID   | $\sigma_{\text{ECSN}}$ | $\alpha$ |
|------|------------------------|----------|
| EC0a | 0.0 km/s               | 1        |
| EC7a | 7.0 km/s               | 1        |
| EC15a| 15.0 km/s              | 1        |
| EC26a| 26.0 km/s              | 1        |
| EC265a| 265.0 km/s            | 1        |
| ECOa | 0.0 km/s               | 5        |
| ECTa | 7.0 km/s               | 5        |
| EC15a| 15.0 km/s              | 5        |
| EC26a| 26.0 km/s              | 5        |
| EC265a|265.0 km/s             | 5        |

Column 1: simulation name; column 2: 1D rms of the Maxwellian natal kick distribution for ECSNe (see sec. 2.2); column 3: values of $\alpha$ in the CE formalism (see sec. 2.3).
considering the mass loss due to neutrinos and by using the formula suggested by Timmes et al. (1996).

Even if only a few per cent of all SN events should be produced by electron-capture reactions in single stars (Poe- larends 2007), this fraction could drastically raise if we consider binary systems (Podsiadlowski et al. 2004). In binary systems the possibility of accreting material by a companion broadens the mass range of progenitor stars in which the electron-capture collapse may occur (Sana et al. 2012; Dunstall et al. 2015).

### 2.2 Natal kicks

The natal kick of a NS is drawn from a Maxwellian velocity distribution

$$ f(v, \sigma) = \sqrt{\frac{2}{\pi \sigma^2}} v^2 \exp \left[ -\frac{v^2}{2\sigma^2} \right], \quad v \in [0, \infty) $$

where $\sigma$ is the one dimensional root-mean-square (1D rms) velocity and $v$ is the modulus of the velocity.

Given the uncertainties on the natal kick distribution, we have implemented in MOBSE the possibility to draw the natal kick from two Maxwellian curves with a different value of the 1D rms: $\sigma_{ECSN}$ and $\sigma_{ECSNe}$, for core-collapse SNe and ECSNe, respectively. $\sigma = 265$ km s$^{-1}$ is adopted as a default value for core-collapse SNe in MOBSE. This value was derived by Hobbs et al. (2005), studying the proper motion of 233 young isolated Galactic pulsars and corresponds to an average natal kick speed of $\sim 420$ km s$^{-1}$.

In this paper, we consider different values of $\sigma_{ECSN}$, ranging from 0 to 265 km s$^{-1}$, to investigate the importance of ECSNe (see Table 1).

### 2.3 Simulations and initial distributions

Here we describe in detail the initial conditions used to perform our population-synthesis simulations. We randomly draw the mass of the primary star ($m_1$) from a Kroupa initial mass function (IMF, Kroupa 2001)

$$ \Psi(m_1) \propto m_1^{-2.3} \quad \text{with} \quad m_1 \in [5 - 150] \, M_\odot. $$

The other parameters (mass of the secondary, period and eccentricity), are sampled according to the distributions proposed by Sana et al. (2012). In particular, we obtain the mass of the secondary $m_2$ as follows

$$ \Psi(q) \propto q^{-0.1} \quad \text{with} \quad q = \frac{m_2}{m_1} \in [0.1 - 1], $$

the orbital period $P$ and the eccentricity $e$ from

$$ \Psi(P) \propto (P)^{-0.55} \quad \text{with} \quad P = \log_{10}(P/\text{day}) \in [0.15 - 5.5] \quad \text{(6)} $$

and

$$ \Psi(e) \propto e^{-0.42} \quad \text{with} \quad 0 \leq e < 1 \quad \text{(7)} $$

respectively.

For the CE phase we have adopted the $\alpha\lambda$ formalism (see Webbink 1984; Ivanova et al. 2013). This formalism relies on two parameters, $\lambda$ (which measures the concentration of the envelope) and $\alpha$ (which quantifies the energy available to unbind the envelope). To compute $\lambda$ we used the prescriptions derived by Claeys et al. (2014) (see their Appendix A for more details) which are based on Dewi & Tauris (2000).

We have run ten sets of simulations, by changing the value of $\alpha$ and that of $\sigma_{ECSN}$ (see Table 1). In particular, we have assumed $\alpha = 1, 5,$ and $\sigma_{ECSN} = 0, 7, 15, 26, 265$ km s$^{-1}$ (corresponding to an average natal kick speed of about 0.11, 23.41, 420 km s$^{-1}$, respectively). Finally, for each set of simulations we considered 12 sub-sets with different metallicities $Z = 0.0002, 0.0004, 0.0008, 0.0012, 0.0016, 0.002, 0.004,$
Figure 2. Distribution of eccentricity (left-hand column) and semi-major axis (right-hand column) for all DNSs (black thin lines) and only for merging DNSs (red thick lines). For each simulation we show the distributions obtained at three different metallicities: $Z = 0.02$ (dotted lines), 0.006 (dashed lines), and 0.0002 (solid lines).
The impact of ECSNe on DNSs

3 RESULTS

3.1 Impact of $\sigma_{\text{ECSN}}$ on DNSs

The left-hand panel of Figure 1 shows all DNSs formed in our simulations as a function of metallicity. It is apparent that the lower $\sigma_{\text{ECSN}}$ is, the higher the total number of DNSs. This is not surprising, because a lower $\sigma_{\text{ECSN}}$ implies a lower probability to unbind the system.

This effect is particularly strong for the simulations with $\alpha = 1$, in which the number of DNSs is $\sim 10 - 25$ times higher if $\sigma_{\text{ECSN}} = 0$ than if $\sigma_{\text{ECSN}} = 265$ km s$^{-1}$. In the simulations with $\alpha = 5$, the number of DNSs is $3 - 6$ times higher if $\sigma_{\text{ECSN}} = 0$ than if $\sigma_{\text{ECSN}} = 265$ km s$^{-1}$. We also note that DNSs form more efficiently if $\alpha = 5$ than if $\alpha = 1$.

The right-hand panel of Figure 1 shows only the DNSs which merge in less than a Hubble time (hereafter: merging DNSs). In the simulations with $\alpha = 5$, we find again a monotonic trend with $\sigma_{\text{ECSN}}$, but the differences are much less significant.

In the simulations with $\alpha = 1$ the number of merging DNSs does not show a monotonic trend with $\sigma_{\text{ECSN}}$: runs with $\sigma_{\text{ECSN}} = 7 - 26$ km s$^{-1}$ produce a factor of $\sim 5$ more merging DNSs than simulations with $\sigma_{\text{ECSN}} = 0$ and 265 km s$^{-1}$. The only exception is represented by very metal-poor stars ($Z = 0.0002$), for which the number of merging DNSs with $\sigma_{\text{ECSN}} = 0$ is similar to the one of systems with $\sigma_{\text{ECSN}} = 7 - 26$ km s$^{-1}$.

This behavior can be easily explained by considering that the merging time ($t_{gw}$) due to GW emission depends on both the eccentricity ($e$) and the semi-major axis ($a$) as

$$t_{gw} = \frac{5}{256 G^3 m_1 m_2 (m_1 + m_2)} c^5 \left(1 - e^2\right)^{7/2},$$

where $c$ is the speed of light, $G$ is the gravitational constant, and $m_1$ ($m_2$) is the mass of the primary (secondary) member of the binary.

Equation 8 implies that more eccentric binaries have a shorter merging time. Moderate natal kicks do not unbind a binary, but increase its eccentricity, shortening its merging time. Since most binaries evolve through processes which tend to circularize their orbits (e.g. tidal forces, mass transfer and CE phase), the natal kicks are a fundamental ingredient to obtain highly eccentric orbits.

This behavior is shown in the left-hand column of Figure 2, where the initial eccentricity distribution of all DNSs is compared with that of the merging DNSs (here “initial” refers to the time when the second NS is formed). A large number of DNSs have initial eccentricity close to zero in run EC0$\alpha$1 (corresponding to $\sigma_{\text{ECSN}} = 0$ and $\alpha = 1$), but only very few of them merge within a Hubble time.

Many DNSs have initial eccentricity close to zero and most of them do not merge within a Hubble time also in run EC0$\alpha$5 (corresponding to $\sigma_{\text{ECSN}} = 0$ and $\alpha = 5$). However, run EC0$\alpha$5 is also efficient in producing DNSs with non-zero eccentricity, which are able to merge within a Hubble time. In contrast, only few DNSs with eccentricity close to zero form in the other eight runs, because of the SN kicks.

We note that the second NS originates from an ECSN in the vast majority of DNSs with eccentricity $e \sim 0$.

The right-hand column of Figure 2 compares the distribution of the initial semi-major axis of all DNSs with that of the merging systems. We see that increasing $\sigma_{\text{ECSN}}$ the widest systems tend to disappear, because they can be disrupted more easily by the natal kicks.

3.2 DNS formation channels and ECSNe

From our simulations we find that the most likely formation channel for merging DNSs is consistent with the standard scenario described in Tauris et al. (2017) (see their Figure 1): first the primary star expands and fills its Roche lobe, transferring mass to the companion; then the primary explodes leaving a NS; when the secondary expands, the system enters CE; after CE ejection, the system is composed of a NS and a naked Helium star and the NS starts stripping its companion; the stripped Helium star undergoes a SN explosion, which is most likely an ultra-stripped SN (Tauris et al. 2013, 2015, 2017); the final system is a close DNS which will merge within a Hubble time.

Figure 3 shows the fraction of merging DNSs which follow the standard scenario we have just described ($f_{\text{std}}$). For $\alpha = 5$, $f_{\text{std}}$ is nearly independent of the metallicity of the progenitor, while it depends on the natal kicks. At low kicks ($\sigma_{\text{ECSN}} \leq 26$ km s$^{-1}$) $>> 80$ per cent of merging DNSs formed

| $Z$ | $\sigma_{\text{ECSN}}$ (km s$^{-1}$) | Percentage of DNSs |
|-----|--------------------------|-------------------|
| 0.006 | 0, 008, 0.012, 0.016 and 0.02 | 10$^6$ binary systems |

Figure 3. The percentage of merging DNSs which follow the standard scenario (see Sec. 3.2) as a function of progenitor’s metallicity. Top: simulations with $\alpha = 1$. Bottom: simulations with $\alpha = 5$. |
via the standard scenario, while if $\sigma_{\text{ECSN}} = 265 \text{ km s}^{-1}$ the percentage lowers to $\sim 60 - 70$ per cent.

For $\alpha = 1$, $f_{\text{ad}}$ depends on both the metallicity and the natal kicks. For a given kick distribution, $f_{\text{ad}}$ is minimum at metallicity $Z \sim 0.0016 - 0.006$ (especially in run EC0$\alpha1$ and EC26$\alpha1$), while for a fixed metallicity $f_{\text{ad}}$ is maximum ($\sim 80 - 90$ per cent) for $\sigma_{\text{ECSN}} = 7 - 26 \text{ km s}^{-1}$.

This behavior confirms that ECSNe are a fundamental process for the formation of DNSs, but what is the fraction of systems undergoing an ECSN? Is ECSN more frequently the first or the second SN of a merging system?

Figure 4 shows the fraction of merging DNSs in which at least one of the two SN explosions is an ECSN. Most merging DNSs ($\sim 50 - 90$ per cent) undergo at least one ECSN in the vast majority of simulations (EC7$\alpha1$, EC15$\alpha1$, EC26$\alpha1$, EC0$\alpha5$, EC7$\alpha5$, EC15$\alpha5$ and EC26$\alpha5$). In the simulation EC0$\alpha1$ ($\sigma_{\text{ECSN}} = 0$ and $\alpha = 1$), ECSNe are important at low metallicity ($Z = 0.0002$) and negligible for intermediate and high metallicity. Only in the simulations with large ECSN kicks (runs EC26$\alpha1$ and EC26$\alpha5$), the fraction of DNSs undergoing at least one ECSN is always less than 50 per cent.

Moreover, in simulations with $\alpha = 5$ the percentage of DNSs which undergo at least one ECSN increases with the progenitor’s metallicity.

Overall, we find that the ECSN is the first SN in the vast majority of merging DNSs. Less than $\sim 10$ per cent of merging DNSs go through an ECSN as second SN, independently of the assumptions done for the natal kicks and for the CE efficiency. This result is in agreement with Chruslinska et al. (2017) and Kruckow et al. (2018) (but see Tauris et al. 2017 for a different argument).

This is likely due to the fact that the first SN explosion occurs before that other processes (e.g. a CE phase) are able to shrink the binary; therefore the system is less bound and it can be more easily disrupted if the natal kick of the newborn NS is too strong. In contrast, the second SN explosion tends to occur after a CE, when the system is usually on a very close and less eccentric orbit, hence it can survive even stronger kicks. Moreover, the fact that the second SN explosion induces a high kick velocity facilitates the formation of highly eccentric orbits, which are more likely to merge via GW emission.

### 3.3 GW170817-like systems

Figure 5 shows the number of GW170817-like systems that form in our simulations. We define as GW170817-like systems those merging DNSs with $M_{\text{rem,1}} \in [1.36, 1.60] M_{\odot}$ and $M_{\text{rem,2}} \in [1.17, 1.36] M_{\odot}$ ($M_{\text{rem,1}}$ and $M_{\text{rem,2}}$ being the mass of the primary and of the secondary NS, assuming effective spin $\leq 0.05$, Abbott et al. 2017a). Because of its large mass ($1.36 - 1.60 M_{\odot}$), the most massive component of GW170817-like systems cannot have formed via ECSN. In other words, at least one of the two SNe must be a core-collapse SN, in order to form a GW170817-like system.

Figure 5 shows that at high metallicity ($Z \gtrsim 0.002$ for $\alpha = 1$ and $Z \gtrsim 0.012$ for $\alpha = 5$) all simulations follow a similar trend independently of the value of $\sigma_{\text{ECSN}}$, while for lower metallicities the number of GW170817-like systems becomes sensitive to the value of $\sigma_{\text{ECSN}}$. In particular, the higher $\sigma_{\text{ECSN}}$ is, the lower the number of GW170817-like systems. Furthermore, in the simulations with $\alpha = 5$ the number of GW170817-like systems increases with decreasing metallicity.

The reason is that at high metallicity the majority of

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**Figure 4.** Top (bottom) panels: fraction of merging DNSs in which the first (second) SN is an ECSN as a function of progenitor’s metallicity. Left-hand (right-hand) panels: simulations with $\alpha = 1$ ($\alpha = 5$).
The impact of ECSNe on DNSs

We have investigated the importance of ECSNe on the formation of DNSs. ECSNe are thought to occur frequently in interacting binaries (Podsiadlowski et al. 2004; Tauris et al. 2017) and to produce relatively small natal kicks (Dessart et al. 2006; Jones et al. 2013; Schwab et al. 2015). We assumed that natal kicks generated by ECSNe (iron core-collapse SNe) are distributed according to a Maxwellian function with 1D rms $\sigma_{\text{ECSN}}$ ($\sigma_{\text{CCSN}}$). For iron core-collapse SNe we assume $\sigma_{\text{CCSN}} = 265$ km s$^{-1}$, according to Hobbs et al. (2005), while for ECSNe we explore five different values of $\sigma_{\text{ECSN}} = 0, 7, 15, 26$ and 265 km s$^{-1}$. We also investigate the impact of common envelope, by considering $\alpha = 1$ and $\alpha = 5$.

We find that the number of simulated DNSs scales inversely with $\sigma_{\text{ECSN}}$. In particular, the largest (smallest) number of DNSs form if $\sigma_{\text{ECSN}} = 0$ ($\sigma_{\text{ECSN}} = 265$ km s$^{-1}$). This effect is maximum for $\alpha = 1$, while it is only mild for $\alpha = 5$.

The number of DNSs merging within a Hubble time also depends on $\sigma_{\text{ECSN}}$, but with a rather different trend depending on the assumed value for $\alpha$. For $\alpha = 5$, the number of merging systems follows the same trend as the total number of DNSs. For $\alpha = 1$ the number of DNS mergers is maximum for $\sigma_{\text{ECSN}} = 7 – 26$ km s$^{-1}$, while it drops by a factor of $\sim 3 – 10$ if $\sigma_{\text{ECSN}} = 0$ and if $\sigma_{\text{ECSN}} = 265$ km s$^{-1}$.

The reason is that very large kicks ($\sigma_{\text{ECSN}} = 265$ km s$^{-1}$) completely break the binary, while moderate kicks ($\sigma_{\text{ECSN}} = 7 – 26$ km s$^{-1}$) leave the binary bound but increase its eccentricity. A larger eccentricity implies a shorter timescale for merger by GW emission, as shown by Peters (1964). In contrast, null natal kicks produce a large number of systems with zero initial eccentricity, which have longer merger times.

A large percentage ($\sim 50 – 90$ per cent) of merging DNSs undergo at least one ECSN explosion in most of our simulations. This percentage drops below 40 per cent only if $\sigma_{\text{ECSN}} = 265$ km s$^{-1}$ (or if $\sigma_{\text{ECSN}} = 0$ km s$^{-1}$, $\alpha = 1$ and $Z > 0.0002$).

In the vast majority of merging DNSs, the ECSN is the first SN occurring in the binary. This happens because, in most cases, the first SN occurs before the binary has shrunk significantly (e.g. by CE) and is easily broken if the kick is too strong.

Finally, we select the simulated DNSs whose mass matches that of GW170817. We call these systems GW170817-like systems. At high metallicity ($Z \geq 0.002$ for $\alpha = 1$ and $Z \geq 0.012$ for $\alpha = 5$) the formation of GW170817-like systems is independent of $\sigma_{\text{ECSN}}$, because most GW170817-like systems form through iron core-collapse SNe, while for lower metallicity most GW170817-like systems undergo at least one ECSN and their statistics depends on $\sigma_{\text{ECSN}}$. These results confirm the importance of ECSNe to understand the properties of merging DNSs.

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Figure 6. Top (Bottom) panels: fraction of GW170817-like systems in which the first (second) SN is an ECSN as a function of progenitor’s metallicity. The left-hand (right-hand) panels are for the simulation with $\alpha = 1$ ($\alpha = 5$).

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