Neutrino-dominated Accretion Flows: A Second Nucleosynthesis Factory in Core-collapse Supernovae and Regulating the Iron Markets in Galaxies

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Abstract

Cosmic metals are widely believed to be produced by supernovae (SNe) and compact-object mergers. Here, we discuss the nucleosynthesis of neutrino-dominated accretion flows (NDAFs) with outflows in the centers of core-collapse SNe (CCSNe), and show that the outflows from NDAFs can have a significant contribution to the $^{56}$Ni abundances of faint explosions if the masses of the progenitor stars are within about 25–50 $M_\odot$. Less-massive progenitor stars can produce more $^{56}$Ni than their more-massive counterparts in the NDAF outflow nucleosynthesis channel. Therefore, we find that the total (i.e., CCSNe and NDAF outflows) $^{56}$Ni mass per CCSN depends only weakly upon the mass of the progenitor star. In terms of metallicity evolution, the ratio of $^{56}$Fe (produced by the decay of $^{56}$Ni) mass to the initial total gas mass can increase by $\sim$1.95 times if the upper limits of the nucleosynthesis yields from NDAF outflows and CCSNe are considered. Our results might have significant implications for the chemical evolution of the solar neighborhood, galaxies, and active galactic nuclei.

Unified Astronomy Thesaurus concepts: Accretion (14); Black hole physics (159); Galaxy chemical evolution (580); Nucleosynthesis (1131); Supernovae (1668)

1. Introduction

Neutrino-dominated accretion flows (NDAFs) in the centers of collapsars or compact-object mergers are the plausible central engine of gamma-ray bursts (GRBs, for reviews, see, e.g., Liu et al. 2017a; Zhang 2018). Because NDAFs around black holes (BHs) with very high accretion rates ($M \sim 0.001–10 \ M_\odot \text{s}^{-1}$) are in a state of high density ($\rho \sim 10^{10}–10^{13} \text{g cm}^{-3}$) and high temperature ($T \sim 10^{10}-10^{14} \text{K}$), photons are fully trapped and neutrino-participation processes intensively occur in the disk, and only neutrinos can escape from the disk’s surface to dissipate the viscous-heating energy (e.g., Popham et al. 1999; Narayan et al. 2001; Kohri & Mineshige 2002; Kohri et al. 2005; Lee et al. 2005; Gu et al. 2006; Chen & Beloborodov 2007; Janiuk et al. 2007; Kawanaka & Mineshige 2007; Liu et al. 2007; Xue et al. 2013). Neutrino annihilation above or below the disk will drive ultra-relativistic jets that may trigger a GRB (e.g., Ruffert et al. 1997; Rosswog et al. 2003; Zalamea & Beloborodov 2011).

In the collapsar scenario, the initial mass-supply rates can keep the accretion processes in the NDAF phase; however, the jets are possibly choked in the envelope of the collapsar, especially for low-metallicity massive progenitor stars. Eventually, the jets might break out to power a GRB if the Blandford–Znajek mechanism (Blandford & Znajek 1977) dominates over neutrino annihilation (e.g., Nakachi et al. 2013; Matsumoto et al. 2015; Liu et al. 2018; Nagatake 2018), unless the hydrogen envelope has been expelled prior to explosion. Still, NDAFs play primordial roles in at least five aspects.

First, most of the neutrinos emitted from the disk do not participate in the annihilations but escape freely; so, NDAFs are important sources of MeV neutrinos produced after the explosion a core-collapse supernova (CCSN). Although the typical fluence is one to two orders of magnitude lower than that of CCSNe, the neutrinos of NDAFs in the Local Group ($\leq 1 \text{Mpc}$) might be detected by the future liquid-scintillator detector Low Energy Neutrino Astronomy and Hyper-Kamio-kande (e.g., Liu et al. 2016, 2017b; Wei et al. 2019). Of course, neutrinos from NDAFs in the centers of CCSNe with different masses, metallicities, and initial explosion energies should contribute to the neutrino background (Wei & Liu 2021a, in preparation).

Second, jet precession driven by an NDAF around a spinning BH (e.g., Blackman et al. 1996; Portegies Zwart et al. 1999; van Putten & Levinson 2003; Reynoso et al. 2006; Lei et al. 2007; Liu et al. 2010) or the anisotropic emission of neutrinos from NDAFs (e.g., Suwa & Murase 2009; Liu et al. 2017b) can release gravitational waves (GWs) with frequencies of $\sim$1–100 Hz, which at a distance of 10 kpc, or even 1 Mpc, might be detected by the Einstein Telescope (ET), the Decihertz Interferometer Gravitational Wave Observatory/big bang Observer (DECIGO/BBO), and ultimate-DECIGO (e.g., Sun et al. 2012; Wei & Liu 2020). Detections of these neutrinos or GWs can confirm the existence of NDAFs and constrain the mass and spin of the central BHs in the collapsar and merger scenarios (e.g., Liu et al. 2017b).

Third, NDAFs feed the central BHs and significantly alter their masses and spins if the outflows are inefficient (e.g., Janiuk & Proga 2008; Song et al. 2015). For example, by using the fall-free approximation (corresponding to a very faint explosion), the initial mass-supply rates can be estimated as...
$\sim 1 \, M_\odot \, s^{-1}$ and the accretion process can last for about 10 s progenitors of $\sim 40 \, M_\odot$; although their physical supply rates might be lower than $1 \, M_\odot \, s^{-1}$, central BHs of $\sim 5 \, M_\odot$ will grow by several solar masses. Stellar-mass BHs should undergo fallback hyperaccretion episodes with different explosion energies just after they are born, or even be immediately kicked from the collapsar’s center (e.g., Zhang et al. 2008). These scenarios provide a possible way to understand the “first (or lower) mass gap” ($\sim 2.5-5 \, M_\odot$) in the stellar-mass BH distribution (Liu et al. 2021). In addition, BH spins might also be significantly changed via hyperaccretion processes. Note that the relative importance of inflows and outflows can affect the lightcurves and luminosities of GRBs and CCSNe (or kilonovae, e.g., Liu et al. 2017a; Song et al. 2018; Song & Liu 2019).

Fourth, strong outflows from BH hyperaccretion systems should continuously inject and resupply gas into the envelope of collapsars, thus increasing the accretion timescale and inducing fluctuations in the accretion rates (Liu et al. 2019). This mechanism can explain the unusually bright, long-lived iPTF14hls (e.g., Arcavi et al. 2017) and some supernovae (SNe) with double-peak lightcurves (e.g., Mazzali et al. 2008).

Fifth, a mass of free protons and neutrons abundantly in NDAFs (especially in the inner regions), and the cooling processes in the outflows should synthesize abundant heavy metals. The synthesis products from NDF outflows are quite different between relatively proton-rich circumstances in collapsars and the neutron-rich conditions in compact-object mergers (e.g., Surman et al. 2006; Liu et al. 2013; Xue et al. 2013; Janiuk 2014; Siegel & Metzger 2017). In this work, we do not consider compact-object mergers, and the neutron-rich condition is irrelevant to our study. Actually, for BH-NDAF systems in the centers of collapsars, the difference of the metallicity of the progenitor stars, i.e., the electron fraction $Y_e$ at the outer boundary, can affect the sorts and yields of the metals arising from NDAF outflows (e.g., Pruet et al. 2004; Surman & McLaughlin 2005; Surman et al. 2006; Liu et al. 2013, 2017b; Xue et al. 2013; Janiuk 2014; Song & Liu 2019).

Type Ia SNe are thermonuclear explosions originating from accretion by white dwarfs (WDs) in close binaries or via double-WD mergers. Some of them are considered “standard candles”, which are used to determine cosmological parameters. They are also believed to be one of the most important nucleosynthesis factories to produce heavy metals, including the iron group (see, e.g., Woosley et al. 1986; Arnett 1996; Höflich et al. 1998; Hillebrandt & Niemeyer 2000).

Massive stars ($\gtrsim 8 \, M_\odot$) undergoing core-collapse at the end of their lives can trigger CCSNe (and hypernovae). The nucleosynthesis (especially $^{56}$Ni) processes in such energetic SNe have been widely studied (e.g., Woosley & Weaver 1986, 1995; Nakamura et al. 2001; Woosley et al. 2002; Heger et al. 2003; Maeda & Nomoto 2003; Fryer et al. 2004; Nomoto et al. 2006; Fujimoto et al. 2007; Maeda & Tominaga 2009; Heger & Woosley 2010; Winteler et al. 2012; Sukhbold et al. 2016; Mösta et al. 2018; Kobayashi et al. 2020, and references therein). It is worth mentioning that $^{56}$Ni might be produced in collapsars powering GRBs (e.g., Woosley & MacFadyen 1999), e.g., GRB 980425 associated with SN 1998bw (e.g., Woosley et al. 1999; Sollerman et al. 2000). In order to explain the observations of SN 1998bw and SN 2003dh, Pruet et al. (2004) first investigated nucleosynthesis in outflows from the inner region of the accretion disk formed after the collapse of a rotating massive star. For more massive stars ($\gtrsim 25 \, M_\odot$), BHs should generally be born in their centers, which will result in hyperaccretion processes. All types of SNe are profoundly crucial to the chemical evolution of galaxies and active galactic nuclei (AGNs; see, e.g., Barth et al. 2003; Dietrich et al. 2003; Maiolino et al. 2003; Kobayashi et al. 2006, 2020; Maiolino & Mannucci 2019). However, there are still some questions regarding metal abundance, such as in the solar neighborhood (e.g., Kobayashi et al. 2020) and for high-metallicity quasars at high redshift (e.g., Onoue et al. 2020).

In this paper, we focus on $^{56}$Ni synthesis in NDAFs with outflows in CCSN scenarios and discuss their contribution to the chemical evolution of galaxies and AGNs. In Section 2, we briefly study NDAFs with different outflow properties and explore their nucleosynthesis conditions, and obtain relations between the total $^{56}$Ni yields and progenitor masses. We briefly estimate the contributions of NDAF outflows and CCSNe to $^{56}$Fe yields and how they affect the chemical evolution of galaxies in Section 3. Conclusions and a discussion are made in Section 4.

### 2. NDAFs with Outflows

#### 2.1. Model

Here we present a simplified NDAF model in the presence of disk outflows. The relation between the accretion rate at any radius $\dot{M}(r)$ and at the outer boundary $\dot{M}_{\text{outer}}$ can be described as a power law (e.g., Blandford & Begelman 1999; Yuan et al. 2012; Yuan & Narayan 2014; Sadowski & Narayan 2015; Sun et al. 2019), which is expressed as

$$\dot{M}(r) = \dot{M}_{\text{outer}} \left( \frac{r}{r_{\text{outer}}} \right)^p,$$

where $r_{\text{outer}}$ is the outer boundary of the disk and can be determined by integrating the BH mass using the density profiles of the collapsar model (e.g., Liu et al. 2018). For a BH of $\sim 5 \, M_\odot$ produced during the collapse of a low-metallicity progenitor star of $\sim 40 \, M_\odot$, $r_{\text{outer}}$ is about 50 $r_g$, where $r_g = G M_{\text{BH}} / c^2$ is the Schwarzschild radius and $M_{\text{BH}}$ is the mass of the BH. The index parameter $p$ determines the strength of the outflow, which is an uncertain parameter for NDAFs. We take the inner boundary of the disk $r_{\text{inner}} \approx r_{\text{ms}} = (3 + Z_2 - \sqrt{3 - Z_0} (3 + Z_2 + 2 Z_2)) r_g$, where $r_{\text{ms}}$ is the marginally stable orbit radius, $Z_1 = 1 + (1 - a_\pm)^{1/3}[(1 + a_\pm)^{1/3} + (1 - a_\pm)^{1/3}]$, $Z_2 = \sqrt{3 a_\pm^2 + Z_1^2}$, and $a_\pm (0 < a_\pm < 1)$ is the dimensionless spin parameter of the BH (e.g., Bardeen et al. 1972; Kato et al. 2008).

We can calculate the structure of a steady and axisymmetric NDAF by considering the dynamic equations outlined by Liu et al. (2010) and Sun et al. (2012).

The total pressure $P$ related to the local net accretion rate is the sum of contributions from four terms: gas pressure, radiation pressure, electron-degeneracy pressure, and neutrino pressure (e.g., Kohri et al. 2005; Liu et al. 2007)

$$P = P_{\text{gas}} + P_{\text{rad}} + P_{e} + P_{\nu},$$

where $P_{\text{gas}}$, $P_{\text{rad}}$, $P_{e}$, and $P_{\nu}$ represent gas pressure, radiation pressure, electron-degeneracy pressure, and neutrino pressure, respectively.
and the energy balance equation related to the local net accretion rate is

\[ Q_{\text{vis}}^+ = Q_{\text{adv}} + Q_{\text{photodis}}^+ + Q_{\nu}, \]

(3)

where \( Q_{\text{vis}}^+, Q_{\text{adv}}, Q_{\text{photodis}}^+ \) and \( Q_{\nu} \) denote the viscous-heating rate, and the cooling rates due to advection, photodisintegration, and neutrino losses, respectively (e.g., Kohri et al. 2005; Liu et al. 2007; Xue et al. 2013). Here we ignore \( Q_{\text{photodis}}^- \) because it is much less than the neutrino-cooling rate in the inner region of the disk (e.g., Janiuk et al. 2004; Liu et al. 2007). The detailed neutrino physics of the above two equations can be found in Liu et al. (2017a). It should be mentioned that the above two equations are both related to the local net accretion rate, so we consider that the equation of state is still satisfied and no cooling rate of the outflows is included in the energy equation. Thus the total energy dissipated by the outflows depends on the difference in the viscous-heating rates at the inner boundary and at the outer boundary. This solution should be better than that found with the method of parameterized entropy (e.g., Surman et al. 2006; Miller et al. 2020) on the descriptions of the disk outflows.

We define the neutrino-cooling factor \( f_\nu = Q_{\nu} / Q_{\text{vis}} \) as well as the advection factor \( f_{\text{adv}} = Q_{\text{adv}} / Q_{\text{vis}} \) (e.g., Chen & Beloborodov 2007; Liu et al. 2017a). \( f_\nu \geq 0.5 \) is considered as the ignition condition for NDAFs. The main ingredients of nucleosynthesis in disk outflows, including the initial density, temperature, and materials liable to synthesis, depend critically upon the state of the disk.

### 2.2. Nucleosynthesis Conditions

In previous NDAF studies, the BH mass was often fixed to \( 3 M_\odot \). However, in the collapsar scenario, the mass of the newborn BH is related to the mass and metallicity of the progenitor (e.g., Fryer 1999; Heger & Woosley 2010). Thus we first calculate the density, temperature, and neutrino-cooling factor of NDAFs with different BH masses by fixing the viscous parameter of the disk to \( a = 0.1 \) and the dimensionless spin parameter to \( a_\ast = 0.9 \).

We then obtain the density profiles of the NDAFs with outflows for various \( M_{\text{BH}} \) and find that the disks are dense enough for nucleosynthesis to occur, even at \( r \approx 50 r_g \) (the requirement of the nucleosynthesis on the density is not very strict). The contours of the disk temperature \( T/(10^{10} \text{ K}) \) and the neutrino-cooling factor \( f_\nu \) in the \( M_{\text{BH}}-r \) plane for four cases are shown in Figures 1 and 2, respectively; Cases I-IV correspond to \( (\dot{m}_{\text{outer}}, p) = (1, 0.8), (1, 0.3), (0.1, 0.8), \) and \( (0.1, 0.3) \), respectively, where \( \dot{m}_{\text{outer}} = M_{\text{outer}}/(M_\odot \text{ s}^{-1}) \). Note that \( p = 0.3 \) and 0.8 denote weak and strong outflows from the disk, respectively.

As shown in Figure 1, the NDAF of Case II has the highest temperature since the corresponding accretion rate is the largest and the outflow is the weakest among the four cases. Nevertheless, in all cases, the temperature at \( r \lesssim 20 r_{\text{ms}} \) is higher than \( 10^{10} \text{ K} \) for \( M_{\text{BH}} \lesssim 100 M_\odot \). The initial temperatures of the outflows are close to the disk temperature and are clearly high enough to trigger and maintain the nucleosynthesis processes. However, the NDAFs around the BHs with \( M_{\text{BH}} \gtrsim 50 M_\odot \) do not satisfy the ignition condition since their \( f_\nu \lesssim 0.5 \) (see Figure 2); that is, such NDAFs with outflows are not ideal for nucleosynthesis.

In whichever case shown in Figures 1 and 2, for low-mass BHs \( (\sim 3-5 M_\odot) \), as the products of neutron star (NS)–NS or BH–NS mergers, the nucleosynthesis is efficient in the outflows from NDAFs, which can power luminous kilonovae. We argue that their lightcurves are similar to SNe with steep decays, named “quasi-SNe” (Song et al. 2018).

#### 2.3. Contribution to \(^{56}\text{Ni}\) yields

Since there is no unique link between CCSN explosions and the central accretion processes in simulations, we adopt initial explosions that are very faint \((\sim 0 \text{ B}, \text{ where } 1 \text{ B} = 10^{51} \text{ erg}) \) and very drastic \((\sim 100 \text{ B}) \) as two extreme cases, corresponding to NDAFs with high accretion rates in the centers of collapsars and violent CCSNe under the conditions of \([\text{Mg/Fe}]=0 \) and...
\[ \frac{[O/Fe]}{[O/Fe]} = 0 \], to roughly describe the upper limits of the total \(^{56}\text{Ni}\) yields.

In the collapsar scenario, based on the above solutions of different BH masses, we can estimate the approximate upper limits of the \(^{56}\text{Ni}\) yields of the outflows from NDAFs. By considering the effects of the BH masses on the density profiles of the progenitors in the fall-free approximation, the initial mass-supply processes via fallback in collapsars last about 10 s, and the rate is about \(1 \, M_\odot \, s^{-1}\) for massive progenitors and decreases subsequently. In the following interval of about 50 s, the mean rate is about 0.1 \(M_\odot \, s^{-1}\) (e.g., Liu et al. 2018; Wei et al. 2019). If the accretion rate at the outer boundary is assumed to equal the supply rate we can obtain the outflow mass under the condition of \(f_c > 0.5\) with \(p\) in the range of 0.3 to 0.8. The efficiency of the synthesis in the outflows is very high; in fact, almost all of the material can be converted into elements not lighter than \(^4\text{He}\) (e.g., Surman et al. 2011; Xue et al. 2013). Surman et al. (2011) considered that up to around 50\% of the material ejected from BH accretion disks will become \(^{56}\text{Ni}\) under some optimal conditions. In contrast, Miller et al. (2020) found that very little \(^{56}\text{Ni}\) was ejected in their simulations. Here we assume that approximately 10\% of the outflow material is synthesized into \(^{56}\text{Ni}\) (e.g., Surman et al. 2011; Song & Liu 2019; Zenati et al. 2020). We verify this assumption by using code describing the nuclear statistical equilibrium in proton-rich environments \((Y_e \sim 0.45\text{--}0.50\); see Seitenzahl et al. 2008). At the final step, we adopt the numerical results of Heger & Woosley (2002) to link the BH mass with the mass of the corresponding low-metallicity progenitor star. Here we follow Heger & Woosley (2002) to consider that the BHs are born in the centers of collapsars for progenitor-star masses \(\gtrsim 25 \, M_\odot\).

Some stars might partially lose their envelopes owing to binary interactions (e.g., Podsiadlowski et al. 2003) or strong winds (e.g., Maeder 1992; Heger et al. 2003); thus, very different outcomes emerge at the end of their lives. For example, the final core structure could be structurally changed even for very massive progenitors in binary interactions; e.g., an NS rather than a BH might be born (e.g., Podsiadlowski et al. 2003). Moreover, rotation may be increasingly important to massive stars (e.g., Fryer & Heger 2000; Fryer & Warren 2004; Heger et al. 2005; Maeder & Meynet 2012), which also seriously affects the mass-supply rate (e.g., Liu et al. 2018). Some massive stars may expel their hydrogen envelopes prior to Ib/c SN explosion via winds or rotation (e.g., Woosley et al. 1993; Yoon & Langer 2005). These above impacts and factors are not considered in this work. It should be mentioned that the NDAF contribution to nucleosynthesis is negligible for stars within \(\sim 8\text{--}25 \, M_\odot\) because if the explosion energies of CCSNe for stars \(\gtrsim 8 \, M_\odot\) are not very different, the mass-supply rates for NSs possessing a crust should be much lower than these for BHs (e.g., Zhang et al. 2008; Liu et al. 2021); thus, fallback accretion is inefficient for NSs. Additionally, for newborn NSs in the collapsar centers, a strong magnetic field will destroy the inner region of the disk and prevent the accretion process, then NDAFs cannot be ignited. Thus NSs will avoid collapse to a BH unless the NS is a critically massive NS undergoing spin down.

Figure 3 shows rough upper limits of the \(^{56}\text{Ni}\) yields from NDAFs with outflows (blue shaded region) and CCSNe (the red and green shaded regions show the conditions of \([\text{Mg/Fe}] = 0\) and \([\text{O/Fe}] = 0\) and explosion energies in the range of \(1\text{--}100\) or \(150\) B) as functions of the progenitor-star mass. The black lines denote the medians of each region.

Figure 3. Rough upper limits of the \(^{56}\text{Ni}\) yields from NDAFs with outflows and CCSNe as functions of the progenitor-star mass. The CCSN data are adopted from Umeda & Nomoto (2008). The black lines denote the medians of these regions. The CCSN data are adopted from Umeda & Nomoto (2008), because it is believed that the abundances of the most metal-poor halo stars satisfy the conditions \([\text{Mg/Fe}] \geq 0\) and \([\text{O/Fe}] \geq 0\), according to observations. That means for \([\text{Mg/Fe}] < 0\) or \([\text{O/Fe}] < 0\), the \(^{56}\text{Ni}\) yields should be less than those shown in Figure 3 (Umeda & Nomoto 2008). It should be mentioned that the shaded regions in Figure 3 just reflect the rough upper limits of the \(^{56}\text{Ni}\) yields; or rather, the ability of CCSNe and NDAFs to synthesize \(^{56}\text{Ni}\), because we set the terms for the fall-free approximation of the density profile, \(p \geq 0.3\), for the NDAF outflows, and \([\text{Mg/Fe}] = 0\) and \([\text{O/Fe}] = 0\) for the CCSNe. More importantly, contrary to energetic CCSNe requiring a high explosion energy, the BH-mass growth (i.e., fallback accretion) favors the condition of a low explosion energy. In other words, there is energy and matter competition between CCSN explosions and BH fallback accretion. Hence, Figure 3 indicates that the upper limits of the total \(^{56}\text{Ni}\) yields should depend weakly upon the explosion energy. Hypernova models can increase \(^{56}\text{Ni}\) yields by ten times or more relative to normal CCSNe (e.g., Nomoto et al. 2004), and have been included to investigate the galactic evolution of SN rates (e.g., De Donder & Vanbeveren 2003). In such energetic explosions, fallback accretion is generally inefficient. As well as the hypernova models (e.g., Kobayashi et al. 2020), we consider that nucleosynthesis in the NDAF outflows in the centers of faint or failed CCSNe is another plausible way to explain observations of the metal abundance in our neighborhood and the chemical evolution of galaxies. Moreover, Kobayashi et al. (2020) estimated that the proportion of failed SNe was perhaps as large as 50\% early in the history of the Galaxy, which might support the consequence of the NDAF outflows on nucleosynthesis.

It should be noted that the space below these regions is allowed for in the NDAFs and CCSNe in Figure 3. The physical reasons are as follows. First, the \(^{56}\text{Ni}\) yields of the outflows must decrease as weak outflows \((p \lesssim 0.3)\) increase the density and temperature of the disk. Second, the area below the
regions of Figure 3 correspond to the $^{56}$Ni yields of CCSNe. In general, previous CCSN studies (e.g., Heger et al. 2003; Fryer 2004) often found that the $^{56}$Ni yields are several to tens of percent of a solar mass. Nevertheless, the contributions of the strong outflows of NDAFs should still be highlighted.

It is obvious that the contributions of NDAFs to $^{56}$Ni yields mainly arise from progenitor stars with masses in the range of 25–50 $M_\odot$, which is comparable to CCSNe of similar masses. In previous work (Song & Liu 2019), we proposed that NDAF outflows are sufficient to power all observed SNe associated with GRBs; however, we did not consider the BH-mass effect. This effect is considered in this work. We find that the total yields are still enough to explain all SN–GRB events, including the luminous ones. Hence, the nucleosynthesis of NDAFs with outflows might be responsible for resolving the crisis of the $^{56}$Ni yields in luminous SNe. The evolution of the BH mass and spin in the hyperaccretion process might be further considered, especially in faint explosions including fallback SNe (Wei et al. 2021b). Moreover, we find that the total $^{56}$Ni yields are insensitive to the progenitor mass. In many previous works, the total $^{56}$Ni yields were often obtained by fitting CCSNe lightcurves. That is, the progenitor mass, and even the metallicity, were constrained by assuming that the $^{56}$Ni yields solely originated from CCSNe. This assumption seems to be invalid since the nucleosynthesis of NDAFs with outflows can produce a considerable amount of $^{56}$Ni. Hence, it might be inappropriate to infer progenitor properties from $^{56}$Ni yields. Additional observational evidence (along with lightcurves) should be adopted to possibly distinguish the properties of progenitor stars.

3. Applications on Iron Products

CCSN lightcurves are mainly driven by the decay of radioactive $^{56}$Ni and its daughter product $^{56}$Co to $^{56}$Fe within half-lives of about 6.077 days and 77.236 days, respectively. In most cases of NDAFs with outflows or CCSNe, the yields of $^{56}$Ni and its isotopes are generally larger than those of $^{56}$Fe and its isotopes. The products from the decay of $^{56}$Ni in collapsars should be revisited to include the nucleosynthesis of NDAFs with outflows.

There are many sophisticated chemical-evolution models that consider CCSNe-relevant chemical enrichment (see, e.g., De Donder & Vanbeveren 2003; Kobayashi et al. 2020). However, all of them have neglected the possibility of chemical enrichment through NDAF outflows in faint explosions. Therefore, in order to highlight the importance of the nucleosynthesis in NDAF outflows as an extra chemical-enrichment source, we consider a simple closed-box chemical-evolution model, which shall be validated by the current state-of-the-art chemical-evolution model of Kobayashi et al. (2020).

Considering a closed-box model for the chemical evolution of the cold gas of star-forming galaxies (e.g., Tinsley 1980; Matteucci 2012), we have the following equations describing the evolution of star formation, gas, and the abundance of element $i$ of interest

$$M_\star = M_\odot / t_\star,$$

$$\frac{dM_\star}{dt} = -\dot{M}_\star + R,$$

$$\frac{d(M_i X_i)}{dt} = -\dot{M}_i X_i + E_i,$$

where $\dot{M}_\star$ is the star formation rate, $M_\odot$ is the gas mass, $t_\star$ is a typical star formation timescale, $R$ is the mass-ejection rate at the end of stellar evolution, $X_i$ is the mass fraction of element $i$, and $E_i$ is the ejection rate of element $i$.

The gas is not only consumed by current star formation but also restored by previously formed stars at the end their lives according to

$$R(t) = \int_{m_{\text{e}}(t)}^{m_{\text{max}}} (m-m_{\text{rem}}) \phi(m) \dot{M} [t - \tau(m)] dm,$$

where $m$ is the stellar mass in units of solar mass, $m_{\text{rem}}(m)$ is the remnant mass, $\tau(m)$ is the lifetime of a star of mass $m$, and $m_{\text{max}}$ is the mass of a star for which $\tau(m) = 1$. To better compare with the model of Kobayashi et al. (2020), we adopt the same Kroupa (2001) initial mass function (IMF) for the number of stars, $dN$, within $dm$ as $\phi(m) \equiv dN / dm \propto m^{-\alpha}$ with $\alpha_1 = 0.3$ for $m_{\text{min}} = 0.01 \leq m \leq 0.08$, $\alpha_2 = 1.3$ for $0.08 \leq m \leq 0.5$, and $\alpha_3 = 2.3$ for $0.5 \leq m \leq 50 = m_{\text{max}}$, which is normalized as $\int_{m_{\text{min}}}^{m_{\text{max}}} m \phi(m) dm = 1$. The remnant mass is given by (e.g., Weidemann & Koester 1983; Iben & Tutukov 1984; Thorsett & Chakrabarty 1999; Pagel 2009)

$$m_{\text{rem}} \approx \begin{cases} 0.106m + 0.446, & 0.5 \leq m < 9 \\ 1.4, & 9 \leq m < 25 \\ 0.24m - 4, & m \geq 25 \end{cases}$$

while the lifetime of a star of mass $m$ with solar metallicity is taken from the work of the Geneva group (Schaller et al. 1992) and approximated by

$$\tau(m) \approx 11.3m^{-3} + 0.06m^{-0.75} + 0.0012 \text{ Gyr}.$$
where \( q_i(m) \) is the fresh stellar yield of element \( i \).

We specifically consider the production of \(^{56}\text{Fe} \) produced via the total decay of \(^{56}\text{Ni} \), i.e., \( i = \text{Fe} \). For an amount of initial metal-free gas with mass \( M_{\text{f,0}} \) and star formation timescale \( t_s = 0.1 \) Gyr, and assuming the median \(^{56}\text{Fe} \) yields shown in Figure 3 to stress the NDAF outflow contribution, we show the mass evolutions of \(^{56}\text{Fe} \) with and without a contribution from NDAFs in Figure 4.

We also illustrate the \(^{56}\text{Fe} \) evolution implied by the Kobayashi et al. (2020) model for the closed-box case in Figure 4. Interestingly, our simple treatment agrees quite well with the results of Kobayashi et al. (2020), while the small difference may be attributed to the more accurate recipe adopted for the stellar lifetimes, i.e., the metallicity-dependent, and/or that developed for delicate chemical enrichment by Kobayashi et al. (2020).

Nevertheless, compared to the CCSNe under the condition of \([\text{Mg}/\text{Fe}] = 0 \), the ratio of \(^{56}\text{Fe} \) mass to the initial total gas mass still could increase by a factor of \( \approx 1.95 \) if NDAFs are considered. Our results depend weakly upon the choice of the popular IMFs, such as those preferred by Cai et al. (2020). This is because these popular IMFs often give similar ratios for \( 8M_{\odot} \leq M_{\text{tot}} \leq 30 M_{\odot} \) stars to heavier ones. Note that the increase factor is indeed in close relationship to the adopted maximum stellar mass, \( m^{\text{max}} \), used to normalize the IMF. For example, the increase factor decreases from \( \approx 1.95 \) to \( \approx 1.55 \) if \( m^{\text{max}} \) increases from 50 \( M_{\odot} \) to 100 \( M_{\odot} \), owing to the deficiency of \(^{56}\text{Fe} \) enrichment through the NDAF outflows in stars more massive than 50 \( M_{\odot} \) (Figure 3).

Just like CCSNe, NDAFs can also produce \( \alpha \) elements. We then estimate the cosmic buildup history of iron and \( \alpha \) elements in the presence of NDAFs. That is, \( \alpha \) elements are produced by CCSNe and NDAFs; SNe Ia, CCSNe, and NDAFs contribute to the iron element. Our estimation procedures are as follows (e.g., Blanc & Greggio 2008; Graur et al. 2015; Maoz & Graur 2017). First, we estimate the SN Ia rate as a function of redshift by adopting the cosmic star formation history (SFH) of Madau & Fragos (2017) and the delay-time distribution of SNe Ia of Maoz & Graur (2017). Second, we adopt the mean iron yield of a SN Ia as \( y_{\text{Ia}} = 0.7 M_{\odot} \) (e.g., Howell et al. 2009; Graur et al. 2015; Maoz & Graur 2017). Third, for the mean iron yield of CCSNe \( y_{\text{CCSN}} \), we do not use the solid lines in Figure 3 since they correspond to an optimistic situation; instead, we follow Maoz & Graur (2017) and assume \( y_{\text{CCSN}} = 0.074 M_{\odot} \). Fourth, for the Kroupa (2001) IMF, the CCSN rate (the NDAF rate is assumed to be the same as the CCSN rate) is simply 0.01 times the cosmic SFH. Fifth, the mean iron yield of NDAFs is estimated by considering the results in Figure 3 and the Kroupa (2001) IMF. That is, the only difference between our calculations and those of Maoz & Graur (2017) is that we take the nucleosynthesis of NDAFs with outflows into consideration. We then evaluate the volumetric iron-mass density \( \rho_{\odot}(z) \) as a function of redshift, i.e., \( \rho_{\odot}(z) = \rho_{\text{CCSN}}(z) + \rho_{\text{Ia}}(z) + \rho_{\text{NDAF}}(z) \), where \( \rho_{\text{CCSN}}(z) \) and \( \rho_{\text{NDAF}}(z) \) are the densities due to SNe Ia, CCSNe, and NDAFs, respectively. Following Equations (5)–(8) in Maoz & Graur (2017), the \( \alpha \)-to-iron abundance ratio is

\[
[\alpha/\text{Fe}](z) = \log \left( \frac{f_{\text{CCSN}}(z) + f_{\text{NDAF}}(z)}{f_{\text{CCSN}}(z = 0.43) + f_{\text{NDAF}}(z = 0.43)} \right),
\]

where \( f_{\text{CCSN}} = \rho_{\text{CCSN}}/\rho_{\odot} \) and \( f_{\text{NDAF}} = \rho_{\text{NDAF}}/\rho_{\odot} \). Note that the lookback time for a redshift \( z = 0.43 \) corresponds to the age of the Sun. Our results are shown in Figure 5, which displays the cosmic evolution of \([\alpha/\text{Fe}](z)\) with or without the contribution of NDAFs. In the presence of NDAFs, \([\alpha/\text{Fe}](z)\) is less sensitive to redshift than that without NDAFs. This is simply because the relative contribution to the iron production of SN Ia (i.e., \( \rho_{\text{Ia}}/\rho_{\odot} \)) decreases considerably at redshifts \( z < 0.5 \) by considering the nucleosynthesis of NDAFs. Our results might contribute to explaining the lack of any cosmic evolution of the flux ratio of Fe II to Mg II in AGNs from low to high redshifts (e.g., Barth et al. 2003; Jiang et al. 2007; Shin et al. 2019).

4. Conclusions and Discussion

We studied NDAFs with outflows in the collapsar scenario and presented their contributions to the nucleosynthesis of CCSNe and the chemical-enrichment histories of galaxies. The main conclusions are as follows.

(i) NDAFs are not only GRB central engines, but also the sources of MeV neutrinos, GWs, and the nucleosynthesis factories in the centers of collapsars and compact-object mergers.

(ii) The nucleosynthesis of NDAFs with outflows is an important supplement to CCSNe. The exact composition of these outflows remains a subject of study in detailed models (see, e.g., Miller et al. 2020; Zenati et al. 2020). By considering the contributions of NDAFs on \(^{56}\text{Ni} \) yields, the lightcurves of CCSNe associated with GRBs could be well explained. In addition, our results indicate that it may be inappropriate to infer progenitor properties from \(^{56}\text{Ni} \) products.

(iii) As well as hypernova models (e.g., Kobayashi et al. 2020), the yields of \(^{56}\text{Fe} \) produced by decay of \(^{56}\text{Ni} \) from NDAF outflows in the centers of faint or failed CCSNe should be considered in the chemical evolution of galaxies and AGNs, which might help to understand the metal abundance in the solar neighborhood and those of high-metallicity quasars at high redshifts.

The energetic CCSN profiles used in the simulations of Umeda & Nomoto (2008) and the data of the final BH mass in Heger & Woosley (2002) are chosen in order to describe the
possibly significant contribution of NDAF outflows on nucleosynthesis in this work. Actually, there are an amount of increasingly sophisticated simulations on CCSNe and their nucleosynthesis processes (e.g., Nakamura et al. 2001; Maeda & Nomoto 2003; Fujimoto et al. 2007, and references therein), which might be referred to produce more precise results regarding heavy-element production using a uniform description of stellar evolution. Recently, we built 1D numerical simulations of CCSNe using Athena++ to investigate the first (or lower) mass gap in the compact-object mass distribution by considering progenitors with different masses, metallicities, and initial explosion energies (Liu et al. 2021). More self-consistent solutions to the nucleosynthesis of CCSNe including NDAF outflows will be done in future works.

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