Why are some gamma-ray bursts hosted by oxygen-rich galaxies?

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Abstract

Theoretically long gamma-ray bursts (GRBs) are expected to happen in low-metallicity environments, because in a single massive star scenario, low iron abundance prevents loss of angular momentum through stellar wind, resulting in ultra-relativistic jets and the burst. In this sense, not just a simple metallicity measurement but also low iron abundance ([Fe/H] $<$ -1.0) is essentially important. Observationally, however, oxygen abundance has been measured more often due to stronger emission. In terms of oxygen abundance, some GRBs have been reported to be hosted by high-metallicity star-forming galaxies, in tension with theoretical predictions. Here we compare iron and oxygen abundances for the first time for GRB host galaxies (GRB 980425 and 080517) based on the emission-line diagnostics. The estimated total iron abundances, including iron in both gas and dust, are well below the solar value. The total iron abundances can be explained by the typical value of theoretical predictions, despite high oxygen abundance in one of them. According to our iron abundance measurements, the single massive star scenario still survives even if the oxygen abundance of the host is very high, such as the solar value. Relying only on oxygen abundance could mislead us on the origin of the GRBs.

Key words: galaxies: abundances – gamma-ray burst: individual: 080517 and 980425

1. Introduction

Observationally, there is a population of gamma-ray bursts (GRBs) that shows 'long' durations ($>$ 2s) of bursts (Kouveliotou et al. 1993). It is widely accepted that 'long' GRB (hereafter just referred to as GRB) emission is emitted from ultra-relativistic jets that are launched at the core collapse of a single massive star. This scenario requires a large angular momentum in the collapsing core to launch such jets (Woosley & Heger 2006). In this scenario, the angular momentum is removed by the stellar wind driven by radiation pressure that depends on the iron abundance (Vink & de Koter 2005). Thus, low iron abundance ([Fe/H]$\lesssim$ -1.0) is favored in this single massive star scenario, because the progenitor with low iron abundance does not lose its angular momentum by the mass loss during its evolution (Yoon et al. 2006). Observationally, oxygen abundance has been used as an indicator of iron abundance rather than iron abundance itself, since oxygen has strong emission lines in the rest-frame optical wavelength. Indeed, optical emission-line diagnostics show that many of the GRB hosts have the subsolar oxygen abundances (Modjaz et al. 2008; Levesque et al. 2010a). However, recent observational efforts to investigate unbiased host samples indicate that GRBs can occur in dusty massive star-forming galaxies (Hashimoto et al. 2010; Perley et al.

2016a; Perley et al. 2016b), implying high oxygen abundance. In fact, some of these host galaxies have been confirmed to show high oxygen abundance approaching the solar value based on the emission-line diagnostics (Hashimoto et al. 2015; Krühler et al. 2015; Stanway et al. 2015). The possible high-metallicity environment of GRBs has also been reported from the absorption system in the optical afterglow (Savaglio et al. 2012).

One possible explanation is the overabundance of oxygen, i.e., a high value of [O/Fe] in GRB host galaxies. In such a case, the oxygen abundance can be as high as the solar value, even if the iron abundance is very low, as expected from the single massive star scenario mentioned above. It is well known that the iron is mainly produced by Type Ia supernovae (SNe Ia) (Tinsley 1979), whereas α elements such as oxygen, neon and sulfur are produced by Type II supernovae (SNe II). The time scale of SNe Ia ($\sim 10^9$ yr) is much longer than that of SNe II ($\sim 10^7$ yr). Therefore it is possible that a very young galaxy has no (or less) experience with chemical enrichment from SN Ia but has contribution from SN II, which results in a high value of [O/Fe] (McWilliam 1997). In fact, the overabundance of oxygen has been confirmed for galaxies with strong emission lines (Izotov et al. 2006), which are probably dominated by very young stellar populations undergoing active star formation. Such may be the case with GRB host galaxies, since many GRBs are hosted by galaxies with young stellar populations (Savaglio et al. 2009). In addition, the top-heavy initial mass function (IMF) also can increase the ratio of α element to iron, because theoretical predictions of elemental yields of SNe II show that [α/Fe] increases with increasing progenitor mass (Wyse & Gilmore 1992; Woosley & Weaver 1995). The single massive star scenario might favor the top-heavy IMF of GRB host galaxies. Therefore, GRB host galaxies could have a high value of [O/Fe]. If so, the oxygen abundances of GRB hosts might not always be a good indicator of iron abundance.

2. Observations

To measure the iron abundance, we obtained a spectrum of the host galaxy of GRB 080517 using the Subaru/Faint Object Camera and Spectrograph (Kashikawa et al. 2002) with a B300 grism and L600 filter covering 4000–6000 Å. The slit was oriented to cover the central part of the host galaxy, GRB position, and neighbor galaxy. The slit width of $1''.0$ corresponds to a resolving power of $R \sim 400$. The total exposure time is 3 hr on source.

In addition, we investigate the 1D spectra of the GRB 980425 host galaxy extracted from the burst position (SN) and WR region that is ∼800 kpc away from the burst position, which were reduced by Hammer et al. (2006). The spectra were obtained with the VLT/FORS2 (600B and 600RI grisms with a resolution $R \sim 1300$) covering 3322-8624 Å (Hammer et al. 2006).

The reference galaxies to the GRB hosts are collected from the Sloan Digital Sky Survey (SDSS), in which gas-phase iron abundances are measured based on the Te method (Izotov et al. 2006). These galaxies are likely biased toward low metallicity, because not only weak [Fe III]λ4658 but also [O III]λ4363 need to be detected. The star-forming galaxies with strong emission lines are biased toward higher star-forming rate and lower metallicity (Mannucci et al. 2010) with young stellar populations (Izotov et al. 2006).

3. Results

Figure 1 demonstrates iron and oxygen abundances of the GRB 080517 and 980425 hosts (colored data points). Abundances measured in the iron-measured SDSS galaxies are indicated by black dots. The abundances are 'total' of elements in a gas phase and dust grains, which are derived by correcting for depletion factors (see Hashimoto et al. 2018 for details). The solar abundances are shown by dashed lines. The error bars of the GRB sample contain the observational errors of the emission-line fluxes and statistical uncertainty of the abundance calculation (0.1 dex) and uncertainty of depletion factors (0.109 dex) (see Hashimoto et al. 2018 for details). In the left panel of Figure 1, the total oxygen and iron abundances of the iron-measured SDSS galaxies are well below the solar value. The $[Fe/H]_{total}$ of the two GRB hosts is comparable to that of the iron-measured SDSS galaxies or still located at the lower part, even though the iron-measured SDSS galaxies are biased toward low metallicity. In the right panel of Figure 1, the iron-measured SDSS galaxies with low $[O/H]_{total}$ (or low $[Fe/H]_{gas}$) reach at $[O/Fe]_{total}$ ∼0.5, which is roughly consistent with the convergence value of [O/Fe] determined by nucleosynthesis of SNe II without any contribution from SNe Ia. The $[O/Fe]_{total}$ of the iron-measured SDSS galaxies decreases with increasing $[O/H]_{total}$ (or increasing $[Fe/H]_{gas}$) down to around the solar value. The GRB 080517 host shows quite high $[O/Fe]_{total}$, which is comparable to the highest values of $[O/Fe]_{total}$ of the iron-measured SDSS galaxies. The lower limit of $[O/Fe]_{total}$ at the position of GRB 980425 is slightly higher than that of the WR region and the solar value.

The total iron abundances of the GRB 080517 host and explosion site of GRB 980425 are well below the solar value, even though the oxygen abundance of the GRB 080517 host is comparable to the solar value. Although the error bars of iron abundances are large, the $[Fe/H]_{total}$ of our sample can be explained by the theoretical predictions ($[Fe/H] \lesssim -1.0$) of the single massive star scenario. Relying only on oxygen abundance could mislead us on the origin of the GRBs.

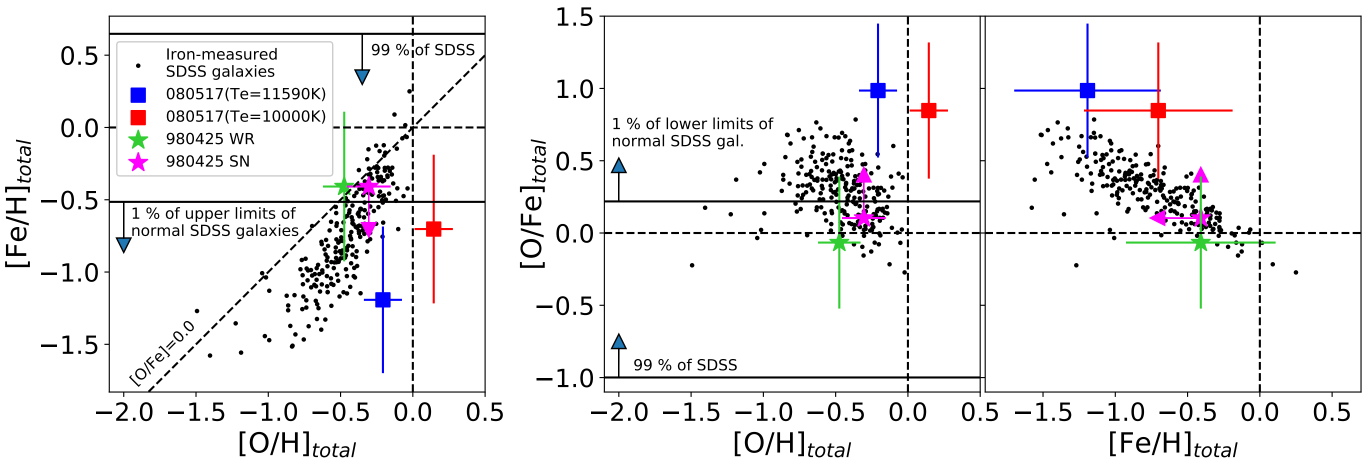

Fig. 1. Iron and oxygen abundances of the GRB 080517 and 980425 hosts (colored data points). Abundances measured in the iron-measured SDSS galaxies are indicated by black dots. The abundances are 'total' of elements in a gas phase and dust grains, which are derived by correcting for depletion factors (see Hashimoto et al. 2018 for details). The solar abundances are shown by dashed lines.

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