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Local analogs of high-redshift galaxies: Interstellar medium conditions

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Abstract. Local analog galaxies play an important role in understanding the properties of high-redshift galaxies. We present a method to select a type of local analog that closely resembles the ionized interstellar medium conditions in high-redshift galaxies. These galaxies are selected based on their locations in the [O III]/Hβ versus [N II]/Hα nebular emission-line diagnostic diagram. The ionization parameters and electron densities in these analogs are comparable to those in $z \simeq 2-3$ galaxies, but higher than those in normal SDSS galaxies by $\simeq$0.6 dex and $\simeq$0.9 dex, respectively. We find that the high sSFR and SFR surface density can enhance the electron densities and the ionization parameters, but still cannot fully explain the difference in ISM condition between nearby galaxies and the local analogs/high-redshift galaxies.

Keywords. ISM: evolution, galaxies: high-redshift, galaxies: ISM

1. Introduction

In the last decade, our knowledge of high-redshift galaxies has improved tremendously from studies of large samples of star-forming galaxies beyond $z \sim 1$ (e.g., Steidel *et al.* 2004). Studies have shown that the interstellar medium (ISM) conditions in high-redshift galaxies are different from those in nearby galaxies. There exists an offset between the high-redshift and the low-redshift star-forming galaxy sequence in the [O III]λ5007/Hβ versus [N II]λ6583/Hα "Baldwin-Phillips-Terlevich" (BPT, Baldwin *et al.* 1981) diagram (e.g., Steidel *et al.* 2014). This offset could be due to higher ionization parameters, harder ionization radiation fields, varying N/O ratios, AGN/shock contributions, and/or selection effects (e.g., Kewley *et al.* 2013; Juneau *et al.* 2014; Salim *et al.* 2015; Shapley *et al.* 2015; Steidel *et al.* 2014).

To study the detailed ISM conditions of high-redshift galaxies, we develop a method to select local analogs of high-redshift galaxies. This type of analog is selected from the MPA/JHU SDSS galaxy catalog (Kauffmann *et al.* 2003). They are located in the high-redshift BPT locus as defined in Steidel *et al.* (2014) (Fig. 1; Bian *et al.* 2016). These analogs share the same properties, in particular the ISM conditions, with the star-forming galaxies at $z \sim 2-3$. Therefore, they could provide us with a local laboratory to study the cause of the extreme ISM conditions in the high-redshift galaxies.

2. ISM Conditions of the Local Analogs of High-redshift Galaxies

We study the ionization parameters and the electron densities in the local analogs using the optical diagnostic lines. Fig. 2 shows the distributions of the ionization parameter (q)

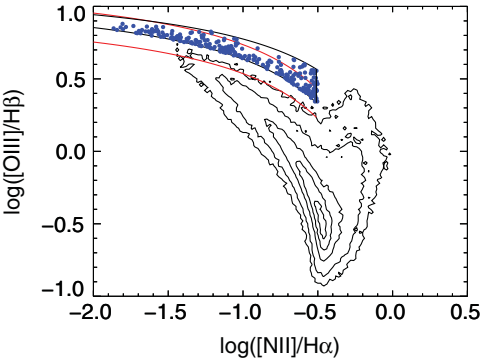

Figure 1. BPT diagram of local star–forming galaxies. The contours represent the distribution of local star-forming galaxies in the BPT diagram and the region bounded by the black solid lines shows selection criteria for our local analogs. The region between the two red lines is the high-redshift star-forming locus in the BPT diagram (Steidel *et al.* 2014). The blue filled points are the local analogs selected in this study.

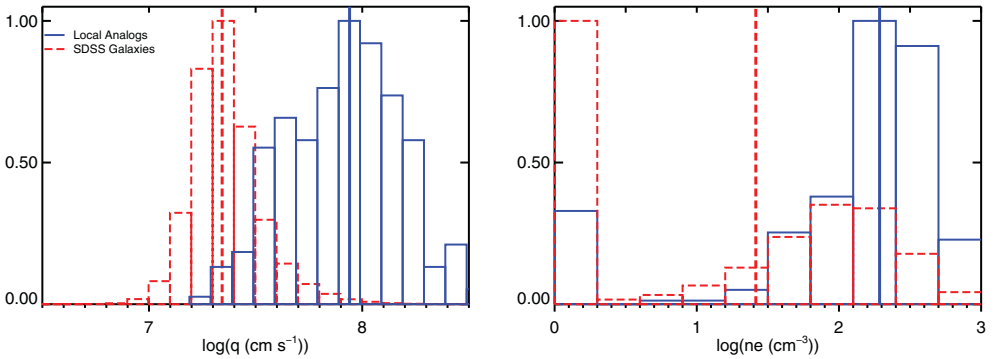

Figure 2. Ionization parameter (left panel) and electron density (right panel) distribution of the local analogs (blue histogram) and the SDSS galaxies (red histogram). The blue solid line and red dashed line represent the median ionization parameter and electron density in the local analogs and the SDSS galaxies, respectively.

and electron density (n_e) in our local analogs of high-redshift galaxies (blue histograms) and the SDSS star-forming galaxies (red histograms). The ionization parameter in our local analogs is about 0.6 dex higher than that in local star-forming galaxies, with a median ionization parameter of $\log(q\ (\mathrm{cm\ s^{-1}})) = 7.94$. This value is in agreement with the ionization parameter found in $z \sim 2-3$ star-forming galaxies (e.g., Nakajima & Ouchi 2014). The median electron density in our local analogs is about 200 $\mathrm{cm^{-3}}$, which is an order magnitude higher than that in local star-forming galaxies, but it is comparable to the electron density in star-forming galaxies at $z \sim 2$ (e.g., Bian *et al.* 2010; Sanders *et al.* 2016).

3. Discussion

In this section, we discuss how the ISM conditions correlate with sSFR and SFR surface density (ΣSFR), and whether the high ionization parameter and high electron density in our local analogs and high-redshift galaxies are entirely caused by the evolution of sSFR and SFR surface density from high redshift to low redshift.

The top panels of Fig. 3 show the median ionization parameters in different sSFR and ΣSFR bins. For the SDSS galaxies, there exists a clear trend whereby the ionization parameter increases with increasing sSFR and ΣSFR. Our local analogs also hold a similar trend. However, for a fixed sSFR and ΣSFR, the ionization parameters in the local analogs are systematically higher than those in the SDSS galaxies by 0.25 dex. The bottom panels of Fig. 3 shows the median electron density in different sSFR and ΣSFR

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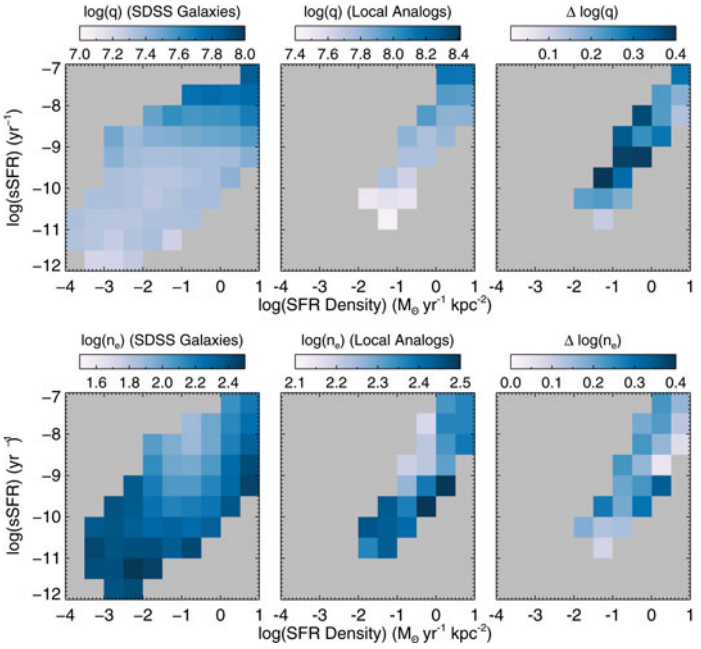

Figure 3. Ionization parameter as functions of sSFR and SFR surface density in the SDSS galaxies (left panel), the local analogs in this study (middle panel), and the ionization parameter difference between the local analogs and SDSS galaxies as functions of sSFR and SFR surface density (right panel). The local analogs have higher ionization parameters than the SDSS galaxies for a given sSFR and SFR surface density. *Bottom*: Same as top panels, but for the electron density.

bins. For SDSS galaxies, we find that the electron density increases with increasing ΣSFR for a fixed sSFR, but deceases with increasing sSFR for a fixed ΣSFR. We find that our local analogs have systematically higher electron density than the SDSS galaxies with similar sSFR and SFR surface density by 0.19 dex.

The high sSFR and high SFR surface density can affect the ionization parameter and electron density in a galaxy. However, they can only partially explain the high ionization parameters and high electron densities in the local analogs and high-redshift galaxies. Therefore, additional mechanisms are required to fully explain the evolution of the ISM conditions from the normal nearby galaxies to the local analogs and high-redshift galaxies.

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