Massive Stars Near and Far
Proceedings IAU Symposium No. 361, 2024
J. Mackey, J. S. Vink, & N. St-Louis, eds.
doi:10.1017/S1743921322003246

Properties of Primitive Galaxies

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Abstract. We report on a study of 9 nearby primitive galaxies observed by Hubble's COS far-UV spectrograph that can serve as templates of high-z galaxies to be observed by JWST. By "primitive galaxies," we mean galaxies having a low stellar mass, $\log(M_*/M_\odot) \leqslant 8$ and low gas metallicity, $\log O/H + 12 \leqslant 8$, whether they are local or at high redshift. We find that far-UV spectra of these galaxies show evidence of hard radiation, including X-rays. Following Thuan et al. (2004), we identify these galaxies as massive X-ray binaries containing a massive accreting stellar black hole. We further find that the lower the metallicity, the higher the probability of extremely strong X-radiation. Following Heger et al. (2003), we suggest that the accreting black hold is produced by direct collapse of stars having initial masses greater than $50\,M_\odot$. The X-radiation produced by black hole disk directly affects the surrounding interstellar medium, and many of these effects are observable in far-UV spectra.

Keywords. techniques: spectroscopic, ultraviolet: galaxies, X-rays: binaries, galaxies: dwarf

1. Introduction

We report on a study of far-UV spectra of nearby primitive galaxies that could give insights into processes operating in the high-z galaxies thought to be responsible for the reionization of the universe. By "primitive galaxies," we mean galaxies having a low stellar mass, $\log(M_*/M_\odot) \leqslant 8$ and low gas metallicity, $\log O/H + 12 \leqslant 8$ and an even lower iron abundance, whether they are local or at high redshift. How does a low metallicity affect the physical properties and evolutionary path of low-metallicity massive stars? One way is through its role in the generation of high-velocity winds of hot, massive stars. Another way is through the presence of hard radiation. X-radiation in extremely deficient stars was first pointed out by Thuan et al. (2004) who found that the three most metal-deficient galaxies are ultra-luminous X-ray emitters (ULX). A ULX is defined by having an X-ray luminosity, $L_x > 1 \times 10^{39}$ erg s^{-1}. They identified these X-ray sources as massive X-ray binaries (MXRB's), each containing a massive, accreting stellar black hole. The optical spectral region also shows evidence of hard radiation. Shirazi & Brinchmann (2012) found that spectra of primitive galaxies observed by the SDSS show *nebular* He II λ4686 in emission, the result of ionization to He III and subsequent recombination. Recently, spectroscopic surveys by Izotov et al. (2021) added six compact star-forming galaxies with $12 + log\mathrm{O/H} = 7.46 - 7.88$ all showing evidence of hard radiation in the form of high-ionization emission lines such as [Ne V].

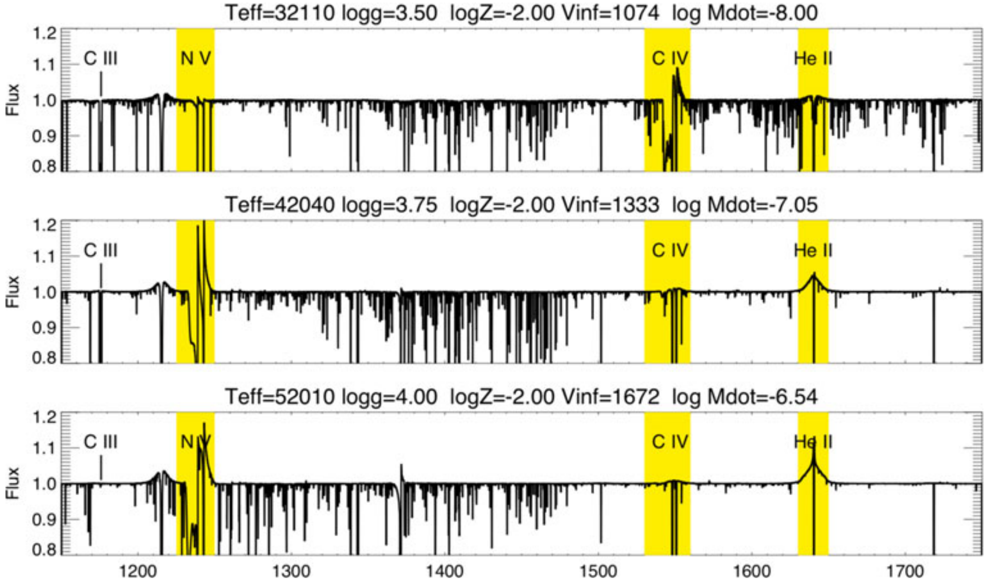

Figure 1. CMFGEN models of the far-UV spectra of main-sequence O-type stars. The stellar parameters are given above each model. They are: effective temperature, log g, log Z, terminal velocity of the wind in km/s, log mass-loss rate in solar masses per year. In a single star, the N V doublet and C IV doublet cannot both be strong, whereas in a star cluster or galaxy, both features can be strong. As He II emission is formed in the stellar wind, It is a broad feature, easily distinguishable from nebular emission which is narrow.

2. Observations of primitive galaxies

The far-UV spectral region is the most informative region for studying stellar winds of primitive stars as it has resonance lines of abundant elements in several ionization stages. There is empirical evidence from far-UV spectra of hot, massive stars in the galaxy and Magellanic Clouds that the strength of the stellar wind increases with increasing metallicity as $Z^{0.7}$ (Vink et al. 2001), but this relation has not been tested below $\log Z \sim 8.0$. We have made predictions of the far-UV spectra of stars based on the grid of non-LTE photospheric models by Lanz & Hubeny (2003; 2007) and unified spectra (photosphere + wind) calculated by Bouret using the CMFGEN code (Hillier & Miller 1998). Figure 1 shows predicted spectra of massive stars showing that even at $\log Z/Z_\odot = -2$, the N V doublet and C IV doublet are still detectable stellar-wind features. When compared to the spectrum of the most metal-deficient galaxy in our sample, I Zw 18-NW, there is qualitative agreement between theory and observation, given that we are comparing the spectra of a galaxy to that of a single star.

Far-UV spectra are similarly informative about the circumstellar, interstellar, and circumgalactic medium of primitive galaxies. Figures 2–3 show the far-UV spectra of 9 galaxies having a nebular oxygen abundances, $\log \mathrm{O/H} + 12 = 7.0 - 8.3$. Spectral regions encompassing the C IV $\lambda\lambda 1548, 1550$ doublet, He II $\lambda 1640$, and O III] $\lambda\lambda 1661, 1666$ are highlighted in yellow. The spectra are arranged in order of increasing oxygen abundance. In Figure 2, covering $\log \mathrm{Z} = 7.0 - 7.8$, not only nebular He II $\lambda 1640$ (IP = 54 eV) is in emission but also nebular C IV doublet (IP=64 eV) in emission superimposed on the stellar spectrum, in which C IV doublet has a P Cygni profile characteristic of a radiatively driven, high-velocity stellar wind. In Figure 3, covering $\log \mathrm{Z} = 7.8 - 8.2$, nebular He II $\lambda 1640$ emission weakens with increasing metallicity to the point that it is

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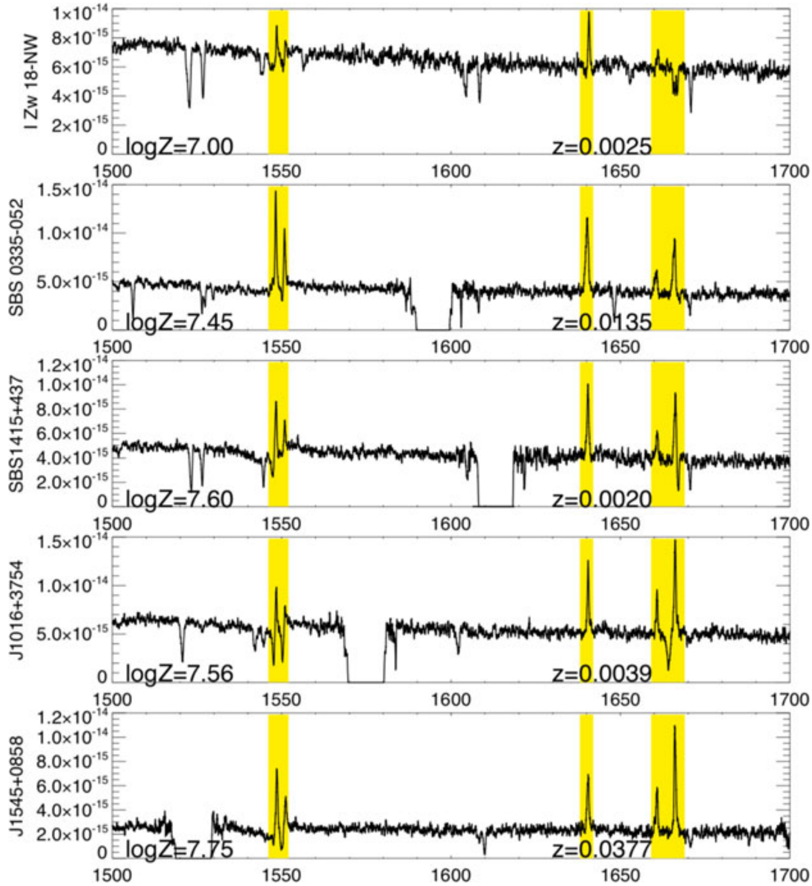

Figure 2. Hubble/COS far-UV spectra of 9 low-Z galaxies. Spectral regions encompassing the C IV $\lambda\lambda 1548, 1550$ doublet, He II $\lambda 1640$, and O III] $\lambda\lambda 1661, 1666$ are highlighted. The galaxy ID is given on the Y-axis of the plot, and its redshift, at the bottom right of the plot. The nebular abundance of oxygen, $\log \mathrm{O/H} + 12$, is listed at the bottom left, denoted as log Z. The spectra are arranged in in order of increasing metal abundance. The spectra of I Zw 18-NWwere obtained directly in programs ID = 11523, 12028 (PI:Green), and most of the others in program ID=14120 (PI:Brinchmann). The two exceptions are SBS 0335-053 and SBS 1415+437, which were obtained from the Hubble archive (ID 15193, PI: Aloisi).

undetectable at $\log \mathrm{Z} = 8.2$. At the same time, broad stellar emission, characteristic of Wolf-Rayet stars, becomes strong in two of the galaxies.

3. Discussion and Conclusions

How are we to understand this metallicity sequence of spectra? To find out, we used CLOUDSPEC, a combination of CLOUDY (Ferland et al. 2017) and SYNSPEC (Hubeny & Lanz 1995) to model the far-UV spectra of galaxies for 3 scenarios. In each scenario, there is a 5 Myr-old primitive stellar population (called "SPop" in Fig. 4) like I Zw 18-NW. In the first scenario (red), there is a dormant black-hole companion or no black hole at all. In the second (green), there is ia black-hole disk radiating X-rays at a rate of 10^{39} erg/s, and in the third (blue), a X-ray source ten times more luminous. Figure 4 shows the results. Nebular emission by He II $\lambda 1640$ is not present when there is no black hole, it is detectable in the case of $L_x = 10^{39}$ erg/s, and it quite strong in the $L_x = 10^{40}$ erg/s case. The C IV doublet is seen in absorption when there is no black hole,

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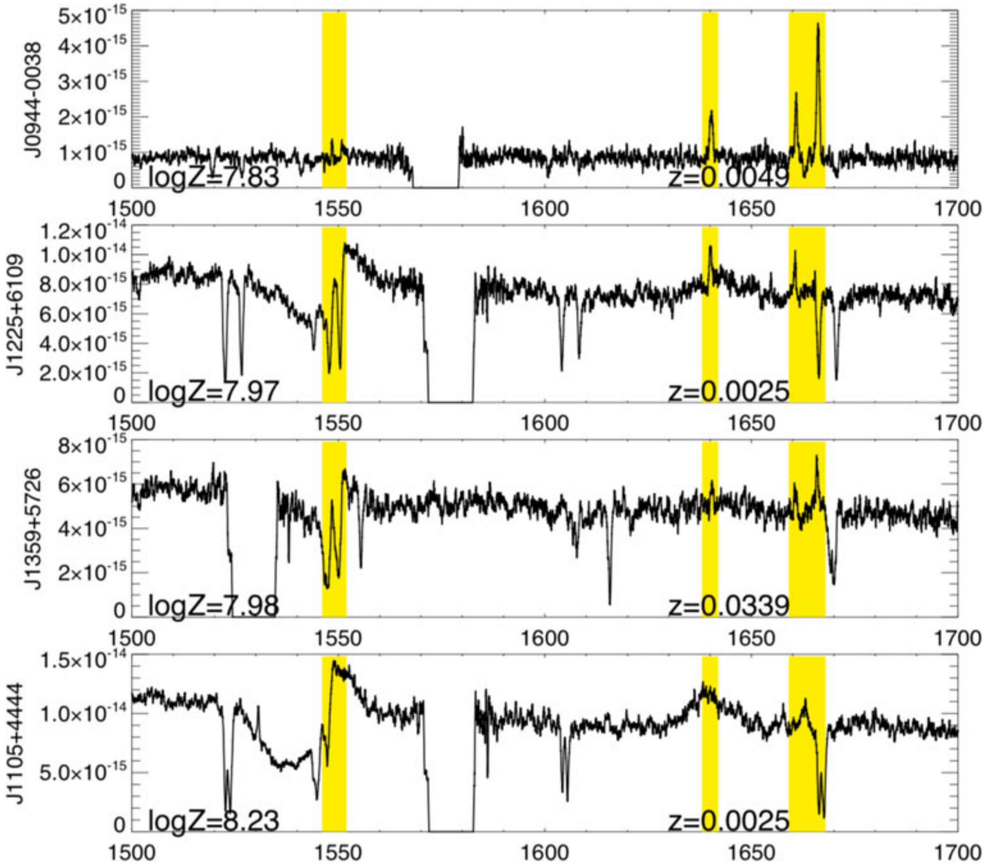

Figure 3. The same as Fig. 2, showing far-UV spectra of higher-z galaxies of our sample.

the absorption lines are partially filled in for the case of $L_x = 10^{39}$ erg/s, and strongly in emission at $L_x = 10^{40}$ erg/s. Although the statistics are limited, we conclude that the presence of C IV emission is associated with galaxies whose metallicity,log $Z \leqslant 7.83$, while nebular He II emission is still present in galaxies until log $Z > 8.0$.

Why should the presence of a black hole be correlated with metallicity? One answer comes from a paper by Heger et al. (2003), titled: "How Massive Single Stars End Their Life". It suggests that stars having a final mass greater than about 40 $M_{\odot}$ collapse directly into a black hole with little to no mass lost in an explosion. Since very low metallicity stars lose very little mass during their lifetime because of such weak stellar winds, their final mass is 80 % of their initial mass (e.g. Groh et al. 2019), so stars formed with an initial mass of 50 $M_{\odot}$ or more will eventually collapse to a massive stellar black hole.

In this interpretation, we are viewing the former secondary orbiting a black hole, which formed from the collapsed primary, and the former secondary is now feeding the black hole via a black hole disk. The black hole disk is hot, particularly at its inner edge where it is 1-2 million degrees, so its emission is centered on the X-ray spectral region. The reason why the disk is hot is because a stellar-mass black hole, as opposed to a supermassive black hole, forms a very deep potential well, so that an accreted material is heated to such high temperatures.

There are still issues to be cleared up, mainly the evolution of massive stars in binary systems, since most hot, massive stars are in binary systems (Sana et al. 2012). Other factors such as the rotation and the C/O ratio must be explored.

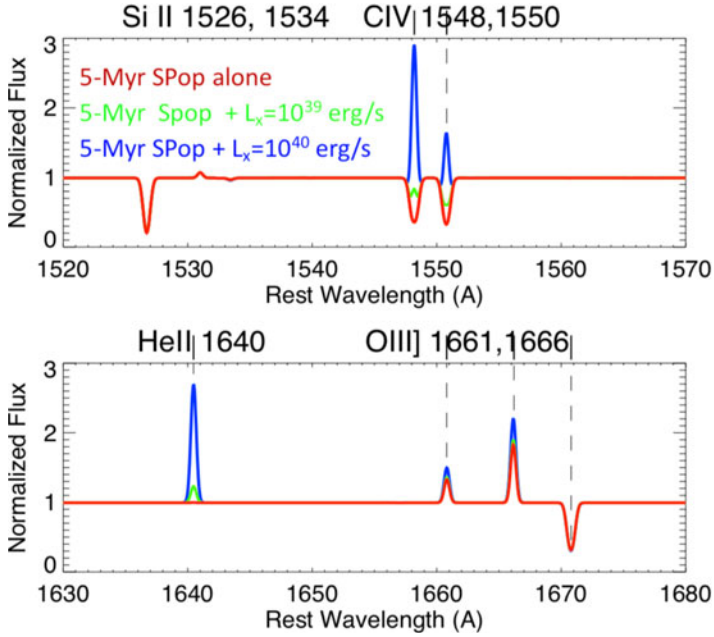

Figure 4. Sample CLOUDSPEC model (Hubeny et al. 2000) of a primitive galaxy like I Zw 18-NW showing the effects of an embedded stellar black hole. Inputs to CLOUDSPEC include: full SED of a stellar cluster at age=5 Myr, log Z = 7.2; BH parameters: Lx as shown, temperature of accretion disk, $T = 10^6$ K; nebular parameters: election density, Ne=10 cm^{-3}, H I column density $=2 \times 10^{21}$ cm^{-2}, covering fraction=0.4, no dust.

We conclude that the properties of massive, extremely low metallicity are extensions of those of low metallicity, e.g. spectral lines are generally weaker, and stellar winds are weaker. However, the final fate and afterlives of primitive massive stars is qualitatively different from those of more metal-rich stars in showing evidence of hard radiation that can best be explained by a hot black hole disk.

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