Dwarf Galaxies: From the Deep Universe to the Present
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Dwarf galaxies at low and high redshift

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Abstract. The overwhelming majority of galaxies in the Universe are dwarf galaxies. But although they are important components in understanding galaxy evolution, these systems are typically too faint to be observed at high redshifts. However, we are able to obtain an unobscured view of early star formation and chemical enrichment in these galaxies at low redshift and low-redshift analogs at high redshift. In this talk, I will review the mass-metallicity relation, the mass-star formation rate relation of galaxies, the classifications of dwarf galaxies, and the importance of dwarf galaxies for both astronomy and physics. Then I will introduce some work in our group on connections among between different types of dwarf galaxies,the mass-metallicity relations and the main sequence relations of dwarf galaxies, using the deep optical and near infrared images and spectra of large dwarf galaxy sample. At the end, I will talk about some projects of dwarf galaxies we are working on, including the spectroscopic survey for compact dwarf galaxies using the LAMOST.

Keywords. galaxies: dwarf, galaxies: evolution, galaxies: fundamental parameters, galaxies: high-redshift, galaxies: starburst.

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1. Scaling relations of galaxies

plasma, even black holes are all made of baryonic matter. The baryons are cycling in and out of galaxies and may lead to a direct impact on the stellar masses, metallicities, and star formation rates (SFRs) of the galaxies. For this reason, the stellar mass-metallicity relation (MZR), the stellar mass - star formation rate relation (the main sequence relation, MSR) serve as observational constraints on models of galaxy evolution, which provides a better understanding of the build-up of galaxies across cosmic time. The presence of an MZR for star-forming galaxies (SFGs) was first observed by Lequeux *et al.* (1979). The MZR in the local universe has been well determined (Tremonti *et al.* 2004) and beyond local universe, the MZR measurements have been reported up to $z \sim 3$. The MZR smoothly evolves from $z \sim 3$ to $z = 0$, with lower-redshift galaxies having higher metallicity at a given stellar mass. SFGs follow a relatively tight MSR was first reported by Brinchmann *et al.* (2004), which is an approximately linear relation between the SFR and the stellar mass of star-forming galaxies. The relation exists at both low and high redshift (Speagle *et al.* 2014). It is a tight relation in the sense that the scatter around the relation is small. The normalisation of the MSR is observed to increase from $z = 0$ to $z \sim 3$, the redshift at which the global star formation rate density peaks (Pan *et al.* 2017).

Although the MZR and MSR provide important observational constraints on models of galaxy formation and evolution, however, most of the MZR and MSR measurements only explore galaxies with $M_{*} > 10^9\,M_{\odot}$, because spectroscopically observing a sufficiently large sample of low-mass galaxies and thus dwarf galaxies is very time-consuming. Deep surveys have shown that galaxy stellar mass functions have steep slopes at the low-mass end, indicating the necessity to study the MZR and MSR of dwarf galaxies, to know **how about the mass-metallicity relation of low dwarf galaxies? what is the evolution of mass-metallicity relation with redshift (especially for dwarf galaxies)?**

2. Dwarf galaxies

Dwarf galaxies are usually defined to be galaxies that are fainter than $M_{\rm B} < -16$ mag ($M_{\rm V} < -17$ mag) and more spatially extended than globular clusters with stellar mass within [10^6 - 10^{10}] $M_{\odot}$ (Tolstoy *et al.* 2009). A dwarf galaxy has a diameter of a few kiloparsec (kpc) while the larger galaxies have diameters that can be expressed in units of 10 kpc.

2.1. *Zoo of dwarf galaxies*

Dwarf galaxies have a wide range of different properties. They span a large mean metallicity range, down the lowest seen anywhere. They also exhibit a range of gas fractions, and density, from no gas all the way to gas dominated. They are also to be seen in a range of proximities to other systems of varying mass. Therefore, according to the diverse morphologies, stellar populations and gas content, they are roughly classified into dwarf elliptical galaxies (dEs), dwarf spheroidal galaxies (dSphs), dwarf irregular galaxies (dIrrs), blue compact dwarf galaxies (BCDs), ultra-faint dwarfs (uFds) and ultra compact dwarf galaxies (UCDs).

- dEs: These dwarf galaxies are low luminosity ($-18 < M_B < -14$), low-surface-brightness elliptical galaxies, dont have a lot of gas left and barely form any stars at the moment. They are typically dominated by an old stellar population, large numbers of which are found in clusters of galaxies, especially in the vicinity of large galaxies. Despite their name, dEs are not really fainter versions of true elliptical galaxies, but are structurally distinct.

- dSphs: They are another type of quiescent dwarf galaxies with more extended morphology than dEs. They contain very old stellar populations, and are almost entirely devoid of gas, in the most extreme cases showing upper limits on their gas mass of $< 1\,M_{\odot}$. There is basically not much difference with dE. The main distinction is based on the magnitude, where dSphs are constrained by $-14 < M_B < -8$. Such that they are fainter than dEs. As deduced from their stellar kinematics, the dSphs are the most dark matter-dominated galaxies known, are particularly intriguing objects that connect the macrophysics of dark matter to its microphysics. Dwarf ellipticals and spheroidals together are also classified as early type dwarf galaxies.

- dIrrs: They are the most common type of galaxy in the Universe, they are not clustered around larger galaxies, but are usually found in isolation in contrast to early type dwarf galaxies. In contrast to the two previous types, dIrrs are still forming stars. They are classified as irregulars due to their isophotes that are not as smooth as the early type galaxies.They are usually loosely structured late-type gas rich systems with varying levels of star formation occurring in a haphazard manner across the galaxy. The velocity field of the H I gas in these systems can be dominated by random motions rather than rotation for the fainter dIs, but for the more massive dIs solid body rotation is clearly seen.

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- BCDs: Just like dIrrs, they have irregular isophotes. However there is a difference with dIrrs since they are generally bluer, more compact and have a higher central surface brightness. Many studies over the past decades have shown that BCDs are metal deficient with a median oxygen abundance of $12 + \log(\mathrm{O/H}) \sim 8.0$ (Kong & Cheng 2002). Apart from their low metallicity, BCDs also exhibit strong bursts of star formation, which are fed by a relatively large amount of gas. Together with the dwarf irregulars, they are referred to as late type dwarf galaxies.

- uFds: Dwarf galaxies of this type have been observed rather recently. These dwarf galaxies have a very low metallicity and are strongly dark matter dominated. It is assumed that they only had very few early star formation.

- UCDs: These are dwarf galaxies with very small effective radii and they are extremely faint. Compared to uFds, they are compacter (with very high stellar densities comparable to globular clusters) and less dark matter dominated. The formation of these galaxies is still poorly understood.

2.2. *Why study dwarf galaxies?*

Dwarf galaxies are small makes them very interesting study objects. The first reason for this brings us back to the early stages of our universe when considering the ΛCDM model since in this model dwarf galaxies are the first structures that were formed. Despite the diversity in morphology, dwarf galaxies contains much less evolved stellar populations than more massive galaxies. With less evolution, the dwarf galaxies provide an environment in the local universe that is closest to the environment in the distant galaxies. Therefore studying these dwarf galaxies could provide unique insights to the early galaxy formation and evolution happened in the early universe.

Dwarf galaxies are the most numerous galaxies in the universe based on modern galaxy mass function. As described above, dwarf galaxies have a wide range of different properties. Thus a study of dwarf galaxy allows us to study star formation over a large range of initial conditions. They are ideal laboratories to study archeology in fundamental astrophysical processes, such as star formation, that drive galaxy evolution.

Due to the fact that they do not succeed in containing most of their initial gas, dwarf galaxies are heavily dark matter dominated. The ratio of dark matter to regular matter in dwarf galaxies are usually very high, they play an important role in addressing the dark matter problem, having already placed interesting constraints on the nature and distribution of dark matter. Particle physicists hope to detect the annihilation of dark matter in dwarf galaxies, more specifically in dwarf spheroidal galaxies since they are even more dark matter dominated.

Although dwarf galaxies provide important constraints on the galaxy formation and evolution, they are much less studied compared to the more massive counterparts due to the their faintness and difficulties to observe in the past. After some decades of effort on studying dwarf galaxies, there are still many fundamental questions need to answered, such as what is the relationship, if any, between different type dwarf galaxies? how about the mass-metallicity relation of low mass (dwarf) galaxies? what is the evolution of mass-metallicity relation with redshift (especially for dwarf galaxies)? In this review, I will talk about our recently work on these questions.

3. Connection among dwarf galaxies

It has been proposed long ago that different types of dwarf galaxies are connected in evolution. A common scenario is that dIrrs evolve into BCDs in several starbursts, enrich the interstellar, exhaust their gas and then fade to gas-free dEs. This scenario is supported by some recent studies where the authors derived the structural parameters

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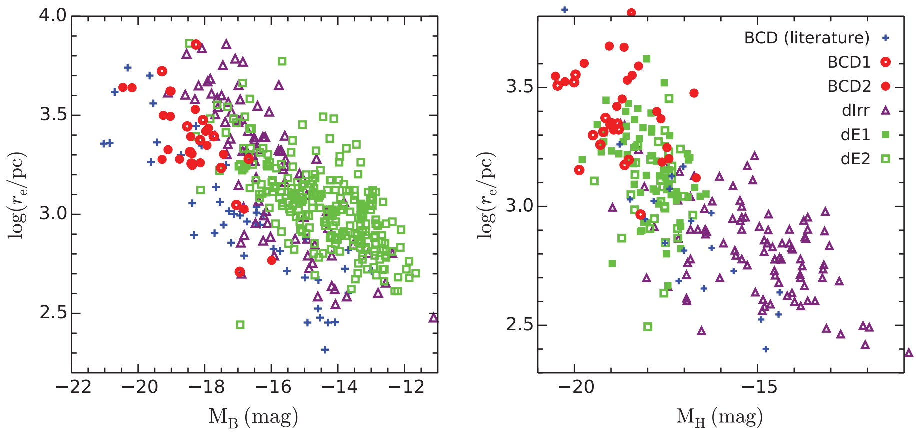

Figure 1. Comparison of structural parameters of BCDs and other type dwarf galaxies. Left: B band. Right: H band. The empty red circles are BCDs with one-component decomposition in this work and marked with BCD1. The solid red circles are BCDs with two-component decomposition and marked with BCD2. The blue crosses are BCDs from Noeske et al. (2003, 2005) and purple triangles are dIrrs from Young et al. (2014) and McCall et al. (2012). The filled green squares represent dEs in the Virgo Cluster from Janz et al. (2014) with one-component decomposition and marked with dE1. The empty green squares are dEs with two-component decomposition and marked with dE2.

of the underlying hosts of blue compact galaxies and found they are consistent with that of dEs and dIrrs (Micheva *et al.* 2013; Meyer *et al.* 2014). However, another recent work (Janowiecki & Salzer 2014) based on similar analysis on optical and near infrared (NIR) images of BCDs found the opposite result that the underlying hosts of BCDs are systematically brighter in the center and more compact than dIrrs. They concluded that, if there is an evolutionary connection between BCDs and dIrrs, there must be significant structural evolution caused by some physical mechanisms.

To probe the underlying structure of dwarf galaxies, deep NIR images are needed as NIR light traces the old stellar populations. The deepest NIR images before our work for dwarf galaxies is only ~ 24 mag arcsec^{-2} (Janz *et al.* 2014) and ~ 23 mag arcsec^{-2} for BCDs (Micheva *et al.* 2013). Recently, CANDELS provide extremely deep and high spatial resolution images in the optical and NIR for galaxies in five sky regions. We use the deepest NIR imaging (~ 26 mag arcsec^{-2}) from the GOODS-N and GOODS-S field to study the structural properties of BCDs (Lian *et al.* 2015b).

With the deep optical and NIR imaging from the CANDELS survey, we extracted the surface brightness profile (SBP) and then fit the profile with one- or two-component Sérsic models. In the left-hand panel of Figure 1, we found similar results to that in Janowiecki & Salzer (2014), the effective radii of the underlying hosts of BCDs in the optical B band are smaller than those of dEs and dIrrs. Since SBPs in the F435W band only reach ~ 26 mag arcsec^{-2}, the structural properties may be affected by nebular emission from the star formation region as discussed in (Micheva *et al.* 2013). Meanwhile, this distinctive distribution may also be due to the luminosities used for the underlying host of BCDs and other dwarf galaxies. Most comparisons in the literature use the luminosity of a galaxy rathe than the underlying host component. This is not representative for BCDs, since their luminosity in the B band includes a significant contribution of the central starburst region.

In the right-hand panel of Figure 1, we compare the structural properties in the H band, the difference between BCDs and other dwarf galaxies seems to be less significant. Furthermore, we find a remarkable agreement between the underlying hosts of BCDs

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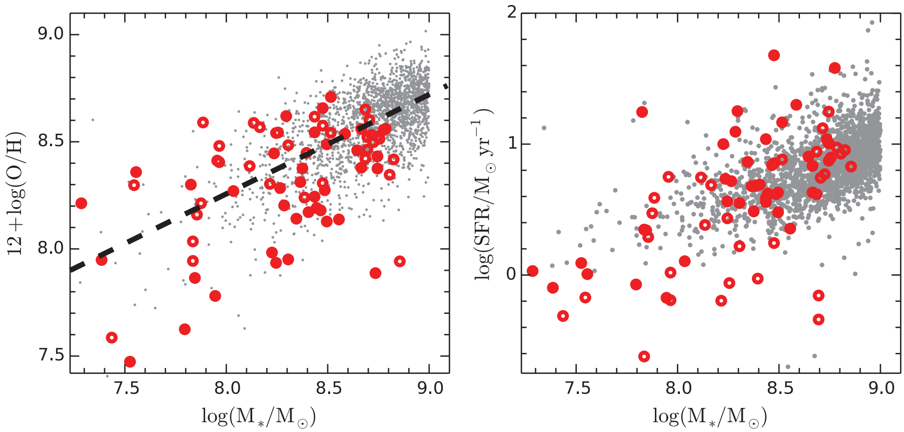

Figure 2. Left: Massmetallicity relation for BCDs. Right: Stellar mass vs. SFR diagram for BCDs. The gray dots are the SDSS BCDs and the red circles are the COSMOS BCDs. The filled circles represent COSMOS BCDs with dust attenuation corrected using the Balmer decrement method.

and dEs in the *H* band. All dwarf galaxies, including dIrrs, seem to follow a similar luminosity-radius relationship, which suggests a unified structural evolution for dwarf galaxies. With deep NIR photometry and detailed surface brightness profile fitting, we conclude that the underlying hosts of BCDs can not be distinguished from those of dEs, and no significant change of structure is needed given the evolutionary connection between BCDs and dEs. In contrast to the underlying hosts, the inner components of BCDs are significantly different from those of dEs. Passive fading from BCDs to dEs may be one of the possible mechanisms that can explain the different inner structure of BCDs and dEs.

4. MZR and MSR of dwarf galaxies

The mass-metallicity relations (MZR) and main sequence relations (MSR) of galaxies have been extensively explored. However, most of these work have focused on massive star-forming galaxies. Using stacking techniques, Andrews & Martini (2013) obtained the MZR of local star forming galaxies down to a few times of $10^7 M_\odot$. Beyond the local universe, Henry *et al.* (2013) were the first to derive the low-mass, intermediate redshift MZR based on 26 emission-line galaxies at $z \sim 0.60.7$. Comparing to the local dwarf galaxies, they found that the metallicity at intermediate redshift is typically lower at a fixed mass, similar to massive counterparts. However, the sample size in these work is relatively small and due to limitation in observations the metallicity determination is less reliable.

To investigate the cosmic evolution of the MZR and MSR at the low-mass end, we select a sample of BCDs at intermediate redshift ($z \sim 0.3$) in the COSMOS deep field (Kong *et al.* 2009) and obtained high quality spectra using Hectospec on MMT (Lian *et al.* 2016). We obtained oxygen abundance measurements for 74 COSMOS BCDs based on the strong-line method from Maiolino *et al.* (2008). For comparison, we also selected a sample of 2023 local BCDs from the Sloan Digital Sky Survey (SDSS) database.

The left-hand panel of Figure 2 shows the MZR of the intermediate redshift COSMOS and local SDSS BCDs. The gray dots represent the SDSS BCDs. The red filled circles represent the COSMOS BCDs with dust extinction corrected using the Balmer decrement method, while the empty circles represent the correction from SED fitting. Interestingly, the MZR of BCDs at the intermediate redshift is fairly consistent with that

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of the local BCDs, suggesting no significant metallicity evolution in these compact dwarf galaxies from redshift $z \sim 0.3$ to ~ 0. Since our metallicity measurements derived by the Maiolino *et al.* (2008) method still suffered large uncertainties, we construct a sample of 48 metal-poor galaxies at $z < 0.14$ selected from 92510 galaxies in the LAMOST survey (Gao *et al.* 2017). These galaxies are identified by their detection of the auroral emission line [O III]λ4363 above the 3σ level. With significant detection of [O III]λ4363, we determine the metallicity using the so-called T_e method, and find that the MZR of metal-poor dwarf galaxies is in good agreement with the MZR in Lian *et al.* (2016).

Besides metallicity, we also obtained the SFR and $D_{\rm n}(4000)$ of BCDs. The right-hand panel of Figure 2 shows BCDs in the massSFR (MSR) diagram. It can be seen that intermediate redshift BCDs exhibit a consistent massSFR (main-sequence) relation with local BCDs. The median deviation of the COSMOS BCDs from the best-fitting line is 0.05 dex which is not significant compared with the dispersion in the main-sequence relation of 0.32 dex. On the other hand, the intermediate redshift BCDs seemed to be younger than the local BCDs, with lower $D_{\rm n}(4000)$ index values. According to the downsizing evolution scenario, low-mass galaxies may experience star formation which decreases less in the recent universe than in massive galaxies. The insignificant deviation in the MZR and MSR between the intermediate redshift and local BCDs may be due to the large scatter in these relations and narrow redshift range.

5. Massmetallicity relation with redshift

The dependence of chemical abundances on galaxy properties across cosmic time provides insight into the physical mechanisms regulating the formation and evolution of galaxies. A strong evolution of the massmetallicity relation has been claimed in high-redshift studies, but with small samples. To investigate the massmetallicity relation of high redshift galaxies (especially for dwarf galaxies) with large sample, we build on a sample of 703 lyman-break analogues (LBAs) in local Universe. LBAs, as introduced by Heckman *et al.* (2005), have about the same properties as high-redshift star-forming galaxies, including luminosity, stellar mass, star formation rate, extinction, and metallicity (Overzier *et al.* 2011). The original selection criteria of LBAs are based on far-ultraviolet (FUV) luminosity ($L_{1530} > 2 \times 10^{10} L_\odot$) and surface brightness ($I_{1530} > 10^9 L_\odot$ kpc^{-2}). Since FUV is sensitive to the dust attenuation, selection based on FUV may bias against dusty galaxies. Hα is also an excellent index of star formation and less sensitive to dust attenuation than FUV. Therefore, we obtain our sample by using Hα luminosity and surface brightness from SDSS Data Release 10 (Lian *et al.* 2015a). Galaxies that satisfy the FUV criteria of LBAs are grouped into the UV selected subsample and others into the non-UV selected subsample.

The left-hand panel of Figure 3 shows the distribution of LBAs in the massmetallicity diagram. Galaxies in the UV subsample are represented as blue circles and those in the non-UV subsample as red asterisks. It can be seen that these two subsamples have a similar distribution in terms of mass and metallicity. The comparison of the MZR between LBAs and these high-redshift SFG samples is presented in the right-hand panel of Figure 3. It can be seen in Figure 3 that the MZR of LBAs is in good agreement with that of SFGs at $z \sim 1.41.7$. Massive LBAs have metallicities similar to that of normal SFGs at $z \sim 0.07$. However, at lower masses, the metallicity discrepancy becomes larger, low-mass systems enrich their interstellar medium on long time-scales and are still converting gas into stars at present time. This is consistent with the downsizing scenario of galaxy population. Massive galaxies at high redshift reach high metallicity, while low-mass systems enrich their interstellar medium on long time-scales and are still converting gas into stars at present time. In terms of downsizing scenario, the local LBAs are less evolved compared to the local SFGs. In addition, the MZ relation is dependent on 4000

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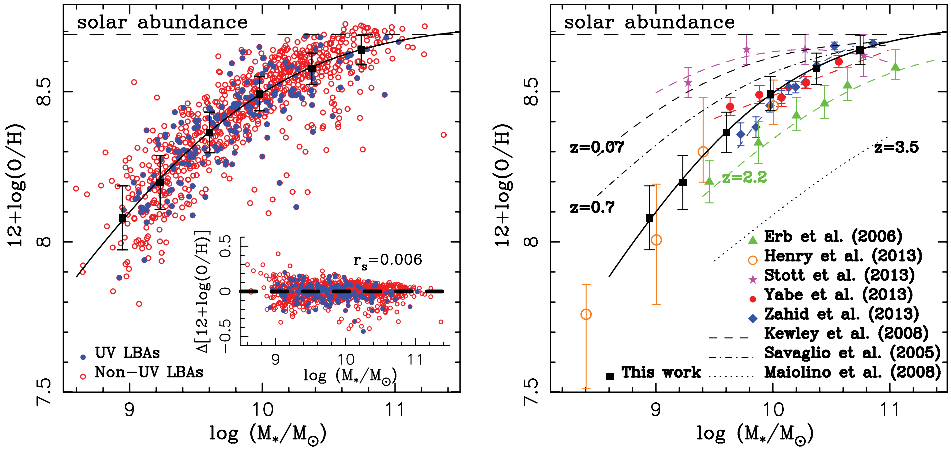

Figure 3. Left: The massmetallicity diagram for galaxies in UV subsample (blue circles) and non-UV subsample(red asterisks).The solid black curve is the best-fitting line and the black squares are binned data. Error bars are the median absolute deviation from median in each bin. The bottom-right inset panel is the metallicity residuals from the logarithmic fit. Right: Comparison of massmetallicity relation of LBAs with the relations at high redshifts.

Å break (i.e. stellar age) with higher metallicity in older galaxies at a given stellar mass. This suggests that the galaxy stellar age plays an important role as a second parameter in the massmetallicity relation of LBAs and even high-redshift SFGs.

6. Projects on dwarf galaxies in the future

With numerous new and forthcoming facilities (e.g., JWST, E-ELT, GMT, TMT, LSST), dwarf galaxies will be studied in much more great detail to understand the early stage of galaxies formation and evolution. Since these facilities will work some years late, alternatively, we can study dwarf galaxies with archival data or those existing equipments. Some project on dwarf galaxies we are working on:

- MZR of intermediate redshift galaxies: The Sloan Digital Sky Survey IV extended Baryonic Oscillation Spectroscopic Survey (SDSS-IV/eBOSS) will observe 195,000 emission line galaxies (ELGs) to measure the Baryonic Acoustic Oscillation standard ruler (BAO) at redshift 0.9. It will provide low signal-to-noise spectra for millions galaxies, including dwarf and metal-poor galaxies, at $z \sim 0.6 - 0.9$. To improve the signal-to-noise of the spectra, we stack spectra of galaxies that are expected to have similar properties, and are studying the low-mass end of MZR and MSR at intermediate redshift.

- LAMOST spectral survey for compact galaxies: The Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST, also called the Guo Shou Jing Telescope) is a special reflecting Schmidt telescope with an effective aperture of 4 m and a field of view of 5°. It is equipped with 4000 fibers, covering a wavelength range of 3800 – 9000 Å at a resolving power $R \simeq 1800$. Since September 2018, a project named "LAMOST spectral survey for compact galaxies" start taking observation. which aims to collect spectra for a statistically complete sample of $\sim 14,000$ low-z compact dwarf galaxies, down to a limiting magnitude of $r \sim 17.8$ mag.

- IFS mapping of dwarf galaxies: Integral field spectroscopy (IFS) is a powerful tool for obtaining the stellar/gaseous velocity field and spatial distributions of physical parameters such as the stellar mass surface density, metallicity and SFR. However, nearly all of these studies concentrated on high-mass galaxies with relatively high metallicities. To map the kinematics and local physical properties of dwarf galaxies with high spatial

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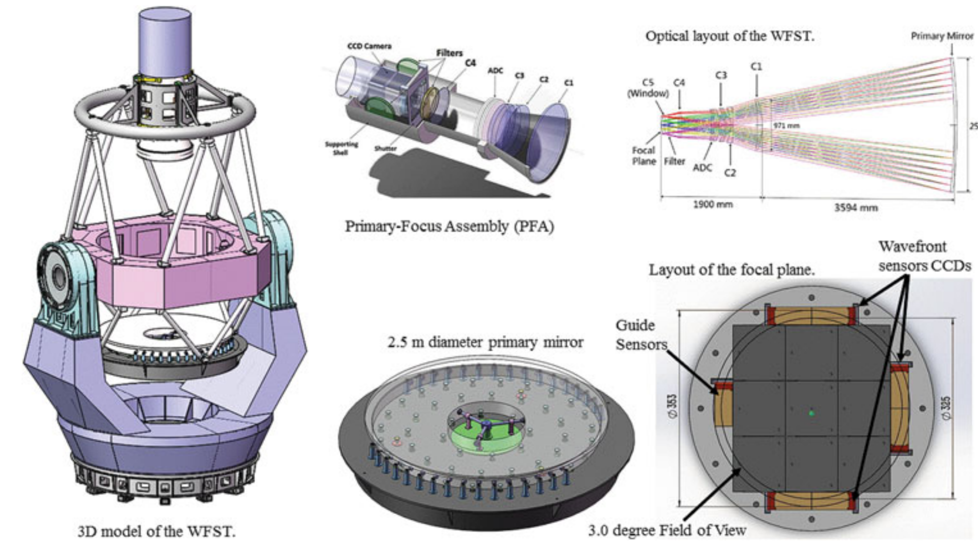

Figure 4. 3D model, primary-focus assembly, optical layout, primary mirror and focal plane of the University of Science and Technology of China (USTC) and Purple Mountain Observatory (PMO) Wide field survey telescope (WFST).

and high spectral resolution, we observe the IFS of dwarf with the Cosmic Web Imager (CWI) instrument at the 200 inch Hale Telescope (P200), and also identify dwarf galaxies observed by SDSS-IV/MaNGA.

- Searching for dwarf galaxies with WFST: Wide field survey telescope (WFST) is a 2.5m wide field survey telescope, which is currently developing by the researchers in University of Science and Technology of China (USTC) and Purple Mountain Observatory (PMO). This facility is characterized by a 2.5-meter primary mirror and a primary-focus camera of a field of view of 7 square degrees. Based on an advanced primary-focus system, the novel optical design will enable the telescope to precisely survey a wide swathe of sky at wide wave bands. The focal plane is equipped with a 0.9 gigapixel mosaic CCD camera, allowing the entire northern hemisphere to be surveyed every three nights. When completed in 2021, the WFST will be the most advanced of its type in the northern hemisphere, gathering valuable observatory data to monitor astronomical events efficiently. WFST will provide high-precision astrometric and photometric catalogs of objects down to $r < 25$ mag, is expected to revolutionize the discovery and study of dwarf galaxies in the Local Group, with important consequences for understanding galaxy formation and evolution.

Acknowledgments

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Discussion

Q1: What is the effect of alpha enhancement and O enhancement in the M-Z relation? (i.e. in UFDs we see that O is enriched, does this shift your points on the y-axis?)

Xu Kong: Alpha enrichment should not really matter much for star-forming galaxies like BCDs.

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