Mock Observations for the CSST Mission: Integral Field Spectrograph–GEHONG: A Package for Generating Ideal Datacubes (Postprint)

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Abstract

We developed a Python package, GEHONG, to simulate three-dimensional spectral datacubes as would be observed by an ideal telescope for the Integral Field Spectrograph of the Chinese Space Station Survey Telescope. This package generates one-dimensional spectra at specific positions according to a set of two-dimensional distributions of the physical parameters of target sources, corresponding to their local physical properties. In this way, it produces a spatially resolved spectral cube of the target.

The two-dimensional distributions of physical parameters, including surface brightness, stellar populations, and line-of-sight velocity, can be modeled either using parametric models or constructed from real observational data and numerical simulation outputs. For the generation of one-dimensional spectra, we have implemented four spectral components: stellar continuum spectra, ionized gas emission lines, Active Galactic Nucleus (AGN) spectra, and stellar spectra. This design enables GEHONG to simulate various classes of targets, including galaxies, AGNs, star clusters, and H II regions.

Full Text

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Mock Observations for the CSST Mission: Integral Field Spectrograph—GEHONG: A Package for Generating Ideal Datacubes Shuai Feng1,2 aa, Shiyin Shen3 aa, Wei Chen3, Zhaojun Yan3, Renhao Ye3 aa, Jianjun Chen4 aa, Xuejie Dai3 aa, Junqiang Ge4 aa, Lei Hao3, Ran Li5,6, Yu Liang3, Lin Lin3 aa, Fengshan Liu4, Jiafeng Lu7 aa, Zhengyi Shao3 aa, Maochun Wu3, Yifei Xiong3, Chun Xu3, Yang Yang3, and Jun Yin3 aa College of Physics, Hebei Key Laboratory of Photophysics Research and Application, Hebei Normal University, Shijiazhuang 050024, China; sfeng@hebtu.edu.cn Shijiazhuang Key Laboratory of Astronomy and Space Science/Guoshoujing Institute of Astronomy, Hebei Normal University, Shijiazhuang 050024, China Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, China; ssy@shao.ac.cn National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China School of Physics and Astronomy, Beijing Normal University, Beijing 100875, China School of Astronomy and Space Science, University of Chinese Academy of Science, Beijing 100049, China Institute for Astronomy, School of Physics, Zhejiang University, Hangzhou 310027, China Received 2025 February 14; revised 2025 May 6; accepted 2025 May 18; published 2026 January 6

Abstract

We developed a Python package GEHONG to mock the three-dimensional spectral datacube under the observation of an ideal telescope for the Integral Field Spectrograph of the Chinese Space Station Survey Telescope. This package can generate one-dimensional spectra corresponding to local physical properties at specific positions according to a series of two-dimensional distributions of physical parameters of target sources. In this way, it can produce a spatially resolved spectral cube of the target source. Two-dimensional distributions of physical parameters, including surface brightness, stellar population, and line-of-sight velocity, can be modeled using the parametric model or based on real observational data and numerical simulation data. For the generation of onedimensional spectra, we have considered four types of spectra, including the stellar continuum spectra, ionized gas emission lines, Active Galactic Nucleus (AGN) spectra, and stellar spectra. That makes GEHONG able to mock various types of targets, including galaxies, AGNs, star clusters, and H II regions. Key words: galaxies: general –techniques: imaging spectroscopy –galaxies: evolution

1. Introduction characterized the detailed kinematic information of stars and gas (Cappellari et al. 2006; Genzel et al. 2011), and uncovered Integral Field Spectroscopy (IFS) has become a powerful observational technique in modern astronomy. Unlike tradi- the outflows driven by Active Galactic Nucleus (AGN) tional slit or fiber spectroscopy, which captures spectral feedback (Cano-Díaz et al. 2012; Venturi et al. 2018). The information at only discrete locations, IFS simultaneously advantages of IFS make it an indispensable tool for obtains a full spectrum at each position within a two- contemporary and future astronomical observations. dimensional (2D) field of view. This results in a three- Modern telescopes are now widely equipped with IFS dimensional (3D) datacube, with two spatial dimensions and instruments, allowing for large-scale spectroscopic surveys of one spectral dimension, enabling spatially resolved studies of galaxies. Key facilities include the Multi Unit Spectroscopic extended astronomical objects, such as galaxies. Compared to Explorer (MUSE) on the Very Large Telescope (Bacon et al. conventional spectroscopic methods, IFS provides a more 2010), the Keck Cosmic Web Imager on the Keck Observatory comprehensive view of the internal structure, kinematics, and (Morrissey et al. 2018), and the Near Infrared Spectrograph on chemical composition of galaxies, making it an essential tool the James Webb Space Telescope (Böker et al. 2022). Several for understanding galaxy formation and evolution. major surveys have utilized IFS to explore galaxy evolution in In recent years, IFS observations have significantly unprecedented detail, including the Calar Alto Legacy Integral advanced our understanding of galaxies. These observations Field Area Survey (Sánchez et al. 2012), the Mapping Nearby have revealed differences in star formation histories and stellar Galaxies at Apache Point Observatory (MaNGA) survey populations among different galaxies (González Delgado et al. (Bundy et al. 2015), and the Sydney-AAO Multi-object 2015; Goddard et al. 2017), demonstrated the impacts of star Integral field spectrograph (SAMI) Galaxy

> Survey (Croom formation on the surrounding ionized gas (Sarzi et al. 2010; et al. 2012). These projects have provided extensive datasets Belfiore et al. 2016), traced the chemical enrichment of that have significantly advanced our understanding of galaxy galaxies (Sánchez et al. 2014; Belfiore et al. 2017), evolution.

The Chinese Space Station Survey Telescope (CSST; Table 1 Zhan 2011, 2021; Gong et al. 2019) is a 2 m space telescope Input Parameters of Config planned to be launched, which shares the same orbit with the Parameters Default Units Description Chinese Space Station (CSS, also known as Tiangong). The wave_min 3000 Å Blue-end of wavelength coverage Integral Field Spectrograph is also one of the key precision wave_max 10500 Å Red-end of wavelength coverage instruments on board the CSST (CSST-IFS), designed for dlam 1.5 Å Wavelength width of each spaxel spatially resolved spectral observations of selected targets. The nx 100   Number of pixels in the spatial dimension (x-axis direction) CSST-IFS has a 6 × 6 field of view with a spatial resolution ny 100   Number of pixels in the spatial dimension of 0.2. It offers a spectral coverage of 3500–10,000 Å with a (y-axis direction) spectral resolution of R   1000. With such excellent spatial dpix 0.1 arcsec Pixel size in the spatial dimension resolution capabilities, especially in the ultraviolet (UV)- optical bands, the CSST-IFS will be a unique instrument for studying the fine structure of galaxies at small scales, such as Sections 3, 4, and 5 describe the generation of onestar-forming regions and the vicinity of supermassive black dimensional (1D) spectral data, 2D maps, and the final 3D holes within the centers of galaxies. datacube, respectively. Finally, we summarize the key points To better understand the CSST-IFS capability, we have in Section 6.

developed a Python package specifically to mock the 3D spectroscopic datacubes of its main scientific targets. The package is named GEHONG (GEnerate tHe data Of iNtegral 2. Overview of Gehong Package field spectrograph of Galaxy), which is dedicated to generating The GEHONG package consists of four modules. The a wide variety of high spatial resolution (0.1 × 0.1) 3D config module defines the format of the IFS data, with datacubes of galactic objects while incorporating as many input parameters listed in Table 1. Under the default settings, necessary physical processes as possible. The 3D datacube the resulting 3D data have a larger field of view, a broader output of GEHONG mocks the ideal scientific data as observed wavelength range, and higher spectral and spatial resolutions by an IFS instrument on a perfect telescope, without including compared to the CSST-IFS observation format, making it more instrumental or observational effects such as seeing, cosmic suitable for the development of CSST-IFS' s scientific procesrays, or background light. These instrumental and observasing system. Based on these settings, the datacube C(x, y,) is tional effects are incorporated by another software of the CSSTa 3D array with dimensions of 100 × 100 × 5000. In addition IFS (Yan et al. 2026), which uses the idealized datacubes to simulating CSST-IFS data, GEHONG can also generate generated by GEHONG as input to produce the corresponding idealized observation data for other IFS instruments by raw CCD images of mock observations.

These mock raw CCD adjusting these parameters. For example, to simulate IFS data images are then the key input of the scientific processing system with a larger field of view, simply modify the field-of-view of the CSST-IFS. Not only that, the 3D datacube output of parameters nx and ny in the config module. GEHONG is also designed to be compatible with the input of the The generation of the IFS datacube is carried out by three IFS exposure time calculator (ETC). With that, ETC can be key modules: spec1d, map2d, and cube3d, as shown in the used to quickly estimate the observation mode of the specific workflow in Figure 1. To generate a datacube for an extended IFS targets and the corresponding signal-to-noise ratio, which is object, such as a galaxy, we first create a series of 2D maps of helpful for the scientific pre-research of the CSST-IFS. physical parameters M(x, y), describing the properties at each Obviously, GEHONG' s output can be applied not only to spatial position within the object. These maps are generated by CSST-IFS-related research but also to other high spatial the map2d module (see Section 4 for details) and include resolution IFS instruments. In fact, similar packages have been stellar population properties (e.g., surface brightness, age, and developed for specific IFS instruments, such as SIMSPIN metallicity), ionized gas properties (e.g., Hα flux and gas- (Harborne et al. 2020) and REALSIM-IFS (Bottrell & Hani 2022) phase metallicity), and kinematics (e.g., line-of-sight velocity for SAMI, MaNGA, and MUSE. However, while these tools are and velocity dispersion). tailored for these instruments, GEHONG remains a versatile tool For each spatial position (xi, yi), the corresponding 1D that can be applied to simulate data for a wide range of IFS spectrum Si( ) is generated using the physical parameters instruments, offering flexibility for research beyond the specific from the 2D map M(x, y). This is implemented by the configurations of these surveys. spec1d module (see Section 3 for details), which synthesizes In this paper, we introduce the design philosophy of the light emitted from stellar populations or ionized gas GEHONG, as well as its detailed implementation process and components to produce the spectrum at each spatial point. The usage scheme. The organization of this paper is as follows: In input parameters required to generate these 1D spectra are Section 2, we present the overall framework of GEHONG. provided in Table 2. For normal galaxies, the spectrum

Figure 1. Schematic diagram of mocking a galaxy IFS data.

includes both the stellar continuum (S star) and the emission (SSP) template spectra as the fundamental building blocks. In lines (S gas) from ionized gas regions. this work, we adopt the E-MILES stellar population models8 Finally, in the cube3d module (see Section 5 for details), (Vazdekis et al. 2016), which provide a broad wavelength these 1D spectra are spatially arranged and combined to form coverage from 1680 to 50000 Å, fully encompassing the the 3D datacube C(x, y,), which represents the complete sensitivity range of CSST-IFS. The E-MILES library also spectroscopic information across both spatial and spectral offers extensive sampling in stellar age and metallicity, enabling dimensions, providing a detailed view of the object' s structure, flexible modeling of a wide variety of galaxy types. gas, and stellar properties at each point.

In GEHONG, the stellar continuum for each spatial pixel is The above provides an introduction to the generation of IFS assembled by combining SSP templates according to a userdata for extended sources (e.g., galaxies and H II regions). For specified star formation history (SFH) and chemical enrichpoint sources (e.g., AGNs, stars, and star clusters), only 1D ment history (CEH). The SFH and CEH can be supplied as 2D spectra need to be inserted at specific positions, eliminating the arrays, where the first column specifies lookback time and the need for constructing 2D maps. Since nearby galaxies are the second column provides either the relative star formation rate primary targets of CSST-IFS, the following sections will focus or the stellar metallicity ([Fe/H]) at each epoch. Only the on galaxies as examples to illustrate the technical details of relative distribution of star formation over time is used to GEHONG. For instructions on using GEHONG, please refer to the appendix. determine the template weights; absolute normalization is not considered. The resulting composite stellar population spectrum is produced by linearly summing the weighted SSP 3. One-dimensional Spectrum templates. Alternatively, for fast and simplified applications, users can input a single age and metallicity. In this case, the 3.1. Continuum of Stellar Population continuum is generated by directly selecting the SSP template The continuum of the stellar population is generated by the whose age and metallicity are closest to the input values. This spec1d.StellarContinuum module. An example spec- dual-mode approach enables both detailed and efficient trum is shown as the red solid line in Figure 2, with the modeling depending on scientific requirements. corresponding input parameters listed in Table 2. The continuum is constructed using single stellar population http://miles.iac.es/

Table 2 Input Parameters of spec1d

Parameters Units Examplea Description Stellar Population Continuum (spec1d.StellarContinuum)

mag mag 15.0 Magnitude in SDSS-r band sfh Gyr 1.0 Star formation history or single age (Gyr) ceh dex −0.3 Chemical enrichment history or single metallicity ([Fe/H]) vel km s−1 100.0 Line-of-sight velocity of stellar continuum vdisp km s−1 100.0 Line-of-sight velocity dispersion of stellar continuum ebv mag 0.1 Dust reddening (EB−V) of stellar continuum

Ionized Gas Emission Line (spec1d.H II_Region)

halpha 10−17erg s−1 cm−2 200 Integral flux of Hα emission line logz dex −0.2 Gas-phase metallicity (log Z / Z) vel km s−1 30,000 Line-of-sight velocity of ionized gas vdisp km s−1 150 Line-of-sight velocity dispersion of ionized gas ebv mag 0.1 Dust reddening (EB−V) of ionized gas

Single Star Spectrum (spec1d.SingleStar)

mag mag 15 Magnitude in SDSS-r band teff K 8000 Effective temperature feh dex −0.1 Metallicity ([Fe/H]) of single star logg cm s−2 3 Surface gravity (log g) of single star vel km s−1 800 Line-of-sight velocity of single star ebv mag

0.1 Dust reddening (EB-V) of single star

AGN Spectrum

Power Law Continuum (spec1d.AGN_Powerlaw) m5100 mag 17 Magnitude between 5050 Å and 5150 Å at the restframe alpha −1.5 Spectrum index of power law vel km s−1 30,000 Line-of-sight velocity of AGN ebv mag 0.1 Dust reddening (EB−V) of AGN

Broad Emission Lines (spec1d.AGN_BLR) hbeta_flux 10−17erg s−1 cm−2 800 Integral flux of Hβ broad line hbeta_fwhm km s−1 5000 FWHM of Hβ broad line vel km s−1 30,000 Line-of-sight velocity of AGN ebv mag 0.1 Dust reddening (EB−V) of AGN

Narrow Emission Lines (spec1d.AGN_NLR) halpha 10−17erg s−1 cm−2 500 Integral flux of Hα narrow line logz dex −0.3 Gas-phase metallicity (log Z / Z) vdisp km s−1 800 Line-of-sight velocity dispersion of narrow emission lines vel km s−1 30,000 Line-of-sight velocity of AGN ebv mag 0.1 Dust reddening (EB−V) of AGN

Fe II Emission Lines (spec1d.AGN_FeII) r4570 0.4 Flux ratio between Fe4570 and Hβ broad line hbeta_broad 10−17erg s−1 cm−2 800 Integral flux of Hβ broad line vel km s−1 30,000 Line-of-sight velocity of AGN ebv mag 0.1 Dust reddening (EB−V) of AGN

Note. a Input parameters of the mock spectrum examples in Figures 2, 3, and 4.

Starting from the assembled stellar continuum, several instrumental resolution of the original observations, with a physical effects are subsequently applied to generate the final wavelength-dependent resolution that corresponds to an output spectrum. intrinsic dispersion of approximately 200 km s−1 in the UV First, we account for the broadening of the stellar continuum ($\lambda < 3541$ Å) and typically less than 100 km s−1 in the optical caused by stellar velocity dispersion. The E-MILES templates and near-infrared. To simulate the internal velocity dispersion already incorporate spectral broadening due to the finite of galaxies, we apply additional broadening only when the

Figure 2. An example of a synthesized spectrum of a normal galaxy. The green line shows the integrated spectrum of the galaxy, the red line represents the stellar population continuum, and the blue line represents the ionized gas emission lines. The spectrum is generated using the spec1d and map2d modules, with the input parameters summarized in Tables 2 and 3. A simple example demonstrating the generation of the galaxy spectrum is provided in Appendix A.1.

input dispersion exceeds the intrinsic template dispersion. In profile of the ith emission line is given by such cases, Gaussian convolution is performed using the fast

Fourier method in logarithmic wavelength space, following the 1 (i) Ei ( ) = exp , (3) implementation in the PPXF package (Cappellari 2017). line , i 2 2 2line , i Second, internal dust attenuation is applied based on the input reddening value EB−V, following the attenuation law of where σline,i is the Gaussian width (in Å) of the ith line. Within Calzetti et al. (2000) and assuming no foreground reddening each spaxel, a constant velocity dispersion σgas is assumed for from the Milky Way. The reddened spectrum is computed as all emission lines. The width σline,i is derived from the ionized gas velocity dispersion σgas (in km s−1) according to S ( ) = S nodust ( ) × e0.921E B V k ( ) , (1) gas line, i = i, (4) where k(λ) represents the attenuation curve. Third, the c spectrum is shifted to the observer' s frame by applying a where c is the speed of light. The composite emission line redshift correction using the input line-of-sight velocity spectrum is constructed by summing over all individual lines (vstellar), with the observed wavelength given by N v stellar S( ) = Li E i ( ) , (5) obs = rest 1 + , (2) i= 1 c where Li is the relative flux of the ith emission line normalized where c is the speed of light. Finally, the spectrum is fluxto the Hα flux. calibrated to match the specified apparent magnitude in the The relative fluxes of the emission lines are determined SDSS-r band. The flux is rescaled accordingly, and the final based on the emission line models from Byler et al. (2017), output is expressed in units of 10−17 erg s−1 Å−1 cm−2. who used Cloudy (Ferland et al. 2013) simulations to model The input parameters for the spec1d.StellarConti- H II regions ionized by young stellar clusters. In these models, nuum module is summarized in Table 2, and a simple guide to the line ratios depend on gas-phase metallicity, the cluster age, its usage is provided in Appendix A.1. and the ionization parameter. For simplicity, we vary only the metallicity, while fixing the cluster age at 106 yr and the 3.2. Emission Lines of Ionized Gas ionization parameter at log U = -2.9 In this work, the emission lines of ionized gas are modeled Dust reddening and redshift correction are applied based on considering only the contribution from H II regions, implethe properties of the ionized gas. Dust reddening is applied mented through the spec1d.H II_Region module. An using the reddening parameter of ionized gas following example spectrum of ionized gas emission is shown as the Equation (1), and redshift correction is performed based on green solid line in Figure 2. the gas line-of-sight velocity following Equation (2). The final The emission lines are generated by representing each line emission line spectrum is then flux-scaled to match a given as a Gaussian profile, with the width reflecting the velocity integrated Hα flux, expressed in units of 10−17 erg s−1 cm−2. dispersion of the ionized gas. We include 84 emission lines 9 The ionized gas emission lines and stellar continuum are treated spanning the wavelength range from 900 to 10500 Å. Each independently. The cluster age used here characterizes typical H II regions emission line is indexed by i, with a central wavelength λi. The and is unrelated to the stellar population ages.

Figure 3. An example of a generated AGN spectrum (black line), decomposed into its four components: the power-law continuum (yellow line), the iron emission line spectrum (green line), the BLR emission lines (red line), and the NLR

emission lines (blue line). The input parameters for each component are summarized in Table 2. A simple example demonstrating the generation of the AGN spectrum is provided in Appendix A.1.

The list of input parameters for ionized gas emission spectrum. In practice, F5100 is derived from the apparent

modeling is provided in Table 2, and an illustrative usage magnitude at 5100 Å in the rest frame. example is presented in Appendix A.1. 3.3.2. Narrow-line Region Spectrum 3.3. Spectrum of Active Galactic Nuclei The NLR spectrum of AGNs (blue line in Figure 3) is Typically, the spectra of AGNs consist of four main generated using the spec1d.AGN_NLR module. The gencomponents: a power-law continuum, a broad-line region eration method follows the approach described in Section 3.2, (BLR) emission line spectrum, a narrow-line region (NLR) with the difference that an AGN-specific NLR model is emission line spectrum, and an iron emission line spectrum. In adopted instead of the H II region model. We employ the our framework, the mock spectra of AGNs are generated by model developed by Feltre et al. (2016), which includes ten separately simulating these four components and then strong optical emission lines. In this model, the line intensity combining them. The power-law continuum, BLR spectrum, ratios depend on several physical parameters, including the NLR spectrum, and iron emission spectrum are generated gas-phase metallicity (log Z /Z), ionization parameter using the modules spec1d.AGN_Powerlaw, spec1d. (log U), metal-to-dust ratio (ξd), neutral hydrogen density AGN_BLR, spec1d.AGN_NLR, and spec1d.AGN_FeII, (log nH / cm 3), and UV photon spectral index (α). In our respectively. The input parameters for each component are framework, only the gas-phase metallicity is treated as a free summarized in Table 2, and a simple example illustrating the parameter, while the other parameters are fixed at log U = -1, usage of these modules is provided in Appendix A.1. ξd = 0.1, log n H /cm 3 = -2, and α = -1.4. The absolute flux In the following subsections, we describe the modeling logic normalization of the NLR spectrum is set by the integrated flux for each of the four spectral components. For each component, of the narrow component of the Hα emission line, and the line dust reddening and redshift effects are individually applied widths are determined by the velocity dispersion of the same following the same procedure as described for the stellar narrow Hα component. The treatment of flux scaling and line continuum in Section 3.1. Since the treatment is identical broadening follows the same procedure as described for H II across all components, we do not repeat these details in each regions in Section 3.2. subsection. 3.3.3. Broad-line Region Spectrum 3.3.1. Power-law Spectrum The BLR spectrum of AGNs (red line in Figure 3) is The power-law continuum component of AGNs (orange line generated using the spec1d.AGN_BLR module. The BLR in Figure 3) is generated using the spec1d.AGN_Power- spectrum is modeled as a collection of broad emission lines, law module. The spectrum is modeled as following a methodology similar to that described in Section 3.2. In contrast to the emission lines from H II regions, F ( ) = F5100 × , (6) only the broad components of the five Balmer lines (Hϵ, Hδ, Hγ, Hβ, and Hα) are included. The relative fluxes among these where F5100 is the flux density at 5100 Å in the rest frame, and lines are fixed based on the observational measurements of α is the spectral index. The overall flux normalization is Mrk 817 (Ilić et al. 2006). The line widths are set according to determined by F5100, which sets the absolute scaling of the the full width at half maximum (FWHM) of the broad Hβ

Figure 4. An example of a synthesized spectrum of a single star. The spectrum is generated using the spec1d.SingleStar module, with the input parameters summarized in Table 2. A simple example demonstrating the generation of the stellar spectrum is provided in Appendix A.1.

emission line, following the common observational conven- In our current implementation, the shape of the stellar

tion. The absolute flux normalization of the BLR spectrum is spectrum is determined by specifying three physical paradetermined by the integrated flux of the broad Hβ component. meters: effective temperature, metallicity, and surface gravity. Other parameters are fixed to typical values, assuming zero rotational velocity and solar α-abundance. The appropriate 3.3.4. Iron Emission Line Spectrum template is selected by first matching the input metallicity and The iron emission line spectrum of AGNs (green line in surface gravity, followed by choosing the template with the Figure 3) is generated using the spec1d.AGN_FeII closest effective temperature. module. The spectral shape is modeled based on the empirical After selecting the optimal template, the effects of dust Fe II emission line template provided by Park et al. (2022), reddening and redshift are applied using Equations (1) and (2), which covers the wavelength range from 4000 to 5600 Å with based on the specified dust reddening and line-of-sight a resolution of approximately 2 Å. The absolute flux normal- velocity. Finally, the absolute flux calibration is performed ization of the Fe II spectrum is determined by the flux ratio by matching the SDSS r-band apparent magnitude, ensuring parameter R4570 = Fe II$ $4570/H\ , whereFeII\ 4570refersthespectrumisnormalizedappropriatelyforobservationaltotheintegrated$ denotes the broad Hβ emission line (Marinello et al. 2016). Given a specified R4570 and the integrated flux of the broad 4. Two-dimensional Maps Hβ component, the absolute flux of the Fe II spectrum is To generate mock IFS data for extended sources such as anchored to the flux scale of the BLR emission. galaxies, it is essential to first construct a series of 2D maps of physical parameters. These 2D maps provide the necessary input for each spaxel, supplying quantities such as stellar 3.4. Single Stellar Spectrum population properties and ionized gas emission strengths, The spectra of single stars are generated using the which are subsequently used by the spec1d module to spec1d.SingleStar module. In Figure 4, we present an generate individual 1D spectra. The accuracy and spatial example of a single stellar spectrum, shown by the red solid structure of these maps directly determine the realism of the line. The input parameters used to generate this spectrum are resulting mock IFS data. summarized in Table 2, and a simple example demonstrating Taking galaxies as an example, the 2D parameter maps can the generation process is provided in Appendix A.1. be broadly divided into two categories. The first category This module employs the stellar spectral templates from describes the stellar component, including quantities required Munari et al. (2005), which cover a wavelength range from 2500 for producing stellar continuum spectra as discussed in to 10500 Å and are available at multiple spectral resolutions. We Section 3.1, such as the surface brightness distribution, the adopt the set with a uniform dispersion of 1 Å pixel−1. The stellar age distribution, and the stellar metallicity distribution. templates span the full Hertzsprung-Russell diagram, with These maps are assembled using the map2d.StellarPoeffective temperatures ranging from 3500, K Teff 47,500, K, pulationMap module, which accepts a set of 2D arrays as surface gravities from 0.0 log g 5.0 , and metallicities input. The second category pertains to the gaseous component, from −2.5 [Fe/H] 0.5. In addition, variations in α-abun- encompassing parameters necessary for modeling ionized gas dance and rotational velocity are also considered in the templates. emission lines as described in Section 3.2, such as the spatial

Figure 5. An example of 2D maps of physical parameters generated using the map2d module, including surface brightness, line-of-sight velocity, and stellar population age. The input parameters used to create the maps are summarized in Table 3, and a simple example demonstrating the generation of the maps is provided in Appendix A.2.

distribution of Hα flux and the gas-phase metallicity. These Table 3 Input Parameters of map2d maps are organized through the map2d.IonizedGasMap module, also based on 2D arrays. Parameter Unit Exampleb Description

To ensure that the 2D parameter maps closely resemble the Sérsic Model (map2d.sersic_map) complex structures observed in real galaxies, we recommend mag mag 15 Integral magnitude of Sérsic model constructing them based on high-spatial-resolution observareff arcsec 4 Effective radius tional data, such as imaging from the Hubble Space Telescope n 1.0 Sérsic index or IFS from MUSE. From such observations, key physical ellip 0.6 Ellipticity maps-including surface brightness distributions, stellar popu- pa degree 30 Position angle lation property maps, and kinematic maps-can be extracted tanh Model (map2d.tanh_map) and used to define the spatial variation of input parameters. Alternatively, outputs from cosmological simulations, such as vmax km s−1 160 Maximum rotational velocity the IllustrisTNG project, can also be utilized to generate rt arcsec 2 Turn-over radius of rotation curve ellip 0.8 Ellipticity detailed 2D distributions. When direct observational or pa degree 0 Position angle simulation data are unavailable, GEHONG provides several commonly used parametric models to facilitate the construc- Gredient Model (map2d.gred_map) tion of 2D maps. In the following subsections, we describe aeffb 9.5 Amplitude at the effective radius three representative parametric models implemented in reff arcsec 6 Effective radius GEHONG. gred −1.2 Gredient ellip 0.4 Ellipticity pa degree 45 Position angle 4.1. map2d.sersic_map Notes. To model the surface brightness distribution of galaxies, a Input parameters of the mock map examples in Figure 5. GEHONG provides the map2d.sersic_map module, which b For the case of the age map, the units of aeff and gred are log yr . generates a 2D Sérsic profile (Sérsic 1963; Graham & Driver 2005). This parametric model can effectively describe a wide range of galaxy light distributions, from exponential disks to de Vaucouleurs bulges. An example of a Sérsic-based and bn is a constant depending on n, determined by surface brightness map is shown in the left panel of Figure 5, (2n) = 2 (2n , bn). (8) with the corresponding input parameters listed in Table 3. A simple code example demonstrating the usage of this module Here, Γ and γ denote the complete and incomplete gamma is provided in Appendix A.2. functions, respectively. The Sérsic profile is described by the following equation The effective radius Re represents the half-light radius, and the Sérsic index n characterizes the profile shape: n = 1 1/n R (x , y) corresponds to an exponential profile typical of disk galaxies, I (x , y) = Ie exp bn 1 , (7) Re while n = 4 corresponds to a de Vaucouleurs profile typical of elliptical galaxies. where Ie is the surface brightness at the effective radius Re, n is The radial distance R(x, y) from the galaxy center (x0, y0) to the Sérsic index that controls the concentration of the profile, a point (x, y) accounts for the galaxy inclination and ellipticity,

and is given by 4.3. map2d.gred_map 2 In addition to surface brightness and velocity, many 2 R min (x , y) R (x , y) = R maj (x , y) + , (9) physical parameters such as stellar age, stellar metallicity, 1 q and gas-phase metallicity exhibit approximately radial gradiwhere q is the minor-to-major axis ratio (related to ellipticity) ents in galaxies (Koleva et al. 2011; Sánchez-Blázquez et al. and θ is the position angle. The coordinates along the major 2014; Belfiore et al. 2017). GEHONG provides the map2d. and minor axes are defined as gred_map module to construct such parameter maps. An example of a radial gradient map is shown in the right panel of R maj (x , y) = (x x 0) cos + (y y0) sin , (10) Figure 5, and the corresponding input parameters are listed in R min (x , y) = (x x 0) sin + (y y0) cos . (11) Table 3. The usage of this module is illustrated with a code To calibrate the surface brightness normalization, the total example in Appendix A.2. apparent magnitude mtot is used. The corresponding total For a galaxy with an inclination angle i, a physical luminosity Ltot for a galaxy following a Sérsic profile can be parameter A at a position (x, y) is described by expressed as (Ciotti 1991) R (x , y) e bn A (x , y) = A (R ,) = A eff + A log , (16) L tot = 2 I (R) R, dR = Ie Re2 2 n (2 n) . (12) Re (bn)2n

4.2. map2d.tanh_map where Aeff is the value of A at the effective radius Re, and ∇A represents the logarithmic gradient of A with respect to radius. For modeling the velocity field of rotating galaxies, The radial distance R(x, y) and the azimuthal angle θ are GEHONG implements the map2d.tanh_map module. This defined as in Equation (9). module generates an axisymmetric rotation map based on a hyperbolic tangent rotation curve (Andersen & Bershady 2013), a common approximation for disk galaxies. 5. Three-dimensional Cube The middle panel of Figure 5 shows an example of such a As mentioned in Section 2 and illustrated in Figure 1, the velocity map, with the input parameters summarized in primary task of 3D datacube generation is to arrange and Table 3. A code example for generating this type of velocity integrate 1D spectra according to the spatial positions provided field is provided in Appendix A.2. by the 2D parameter maps. In practice, this is accomplished For galaxies with an inclination angle approximately given using the cube3d module. by i arccos (1 q), where q is the axis ratio, the line-ofsight velocity at a position (x, y) on the galaxy plane is 5.1. Extended Source expressed as (van der Kruit & Allen 1978) V (x , y) = Vsys + Vc (R) cos sin I , (13) For extended sources such as galaxies, the mock datacube is constructed by generating a 1D spectrum at each spatial where Vsys is the systemic recession velocity, Vc(R) is the pixel based on the local physical parameters. Specifically, intrinsic rotational velocity at radius R, and f is the azimuthal given a 2D map M(x, y), at each position (xi, yi), we mock a angle in the galaxy plane. 1D spectrum Si( ) according to M(xi , yi). This spectrum is The spatial coordinates (x, y) are related to (R, f) through then assigned to C(xi , yi ,) in the 3D datacube. By repeating the expressions given in Equation (9). The azimuthal angle f is this process over all spatial pixels, we obtain the full mock determined by datacube C(x, y,). The input to the cube3d module (x x 0) sin + (y y0) cos consists of the classes generated by the map2d module. cos = , (14) The spectrum of a galaxy typically consists of both stellar R (x , y) continuum and ionized gas emission lines. Accordingly, the where (x0, y0) is the galaxy center and θ is the position angle. 2D maps used for the mock of the datacube should include The intrinsic rotational velocity Vc(R) is modeled by a information on both stellar populations (e.g., stellar population hyperbolic tangent function age and metallicity) and ionized gas properties (e.g., Hα R emission line flux and gas-phase metallicity). If the mocked Vc (R) = Vmax tanh , (15) galaxy does not exhibit significant emission lines, as is typical Rt for early type galaxies, only stellar population maps are where Vmax is the maximum rotational velocity, and Rt is the required. Conversely, when mocking pure emission-line turnover radius at which the rotation curve flattens (Andersen sources, such as H II regions, only ionized gas maps need to & Bershady 2013). be provided.

The above procedure applies to target sources with instrument optimization for CSST-IFS, we have developed relatively simple structures. For more complex cases, it is GEHONG, a Python package designed to mock IFS datacubes necessary to decompose the target into several simpler for various astrophysical targets under idealized observacomponents. The datacube of each component is mocked tional conditions. separately and then combined to obtain the final datacube of The GEHONG package adopts a modular architecture for the target source. For example, to mock a galaxy exhibiting constructing synthetic IFS data, consisting of three main strong ionized gas outflows, the system should be divided into modules. The spec1d module generates 1D spectra at at least two parts: a main galaxy and an outflowing ionized gas individual spatial positions based on input physical paracomponent. The main galaxy datacube, including both the meters, including apparent magnitude, stellar population age stellar continuum and the normal ionized gas emission lines, is and metallicity, emission line fluxes, gas-phase metallicity, mocked following the method described in the previous line-of-sight velocity, and velocity dispersion. It supports the paragraph. The outflow component is treated as a pure modeling of stellar population continua, ionized gas emission emission-line source, requiring only the mock of ionized gas lines, AGN spectra, and single-star spectra. The map2d spectra. After generating the individual mock datacubes for the module constructs 2D distributions of physical parameters, main galaxy and the outflow, they are combined to produce the either through parametric models–such as the Sérsic model, final datacube representing the galaxy with strong gas rotating disk model, and gradient model–or from useroutflows. defined inputs. Finally, the cube3d module assembles the

3D datacube by assigning 1D spectra to spatial pixels, 5.2. Point Source enabling the mock of both extended sources, such as galaxies, and compact sources such as AGNs. In addition to extended sources, GEHONG also supports the mock of point sources, such as AGNs or individual stars. For Acknowledgments point sources, the mock datacube is constructed by assigning a 1D spectrum to a specific spatial pixel, without any spatial The authors thank the anonymous referee for their extension. In the current implementation, no point-spread constructive comments and suggestions, which helped function (PSF) convolution is applied during this assignment, improve the quality of this manuscript. This work is supported and the surrounding spaxels remain empty. by the CSST scientific data processing and analysis system of The GEHONG framework is designed to mock datacubes as the China Manned Space Project. S.F. acknowledges support they would be observed by an idealized telescope, assuming from the National Natural Science Foundation of China perfect optics without PSF blurring, detector noise, or other (NSFC, grant No. 12103017), Natural Science Foundation of instrumental effects. It focuses on modeling the intrinsic Hebei Province (No. A2025205037), and the Project of Hebei spatial and spectral properties of target sources. The simulation Provincial Department of Science and Technology (No. of realistic observational effects, such as replicating the actual 226Z7604G). S.S. thanks research grants from the Shanghai performance of CSST-IFS, is handled by another dedicated Academic/Technology Research Leader (22XD1404200), the software (Yan et al., in preparation), which incorporates National Key R&D Program of China (Nos. 2025YFF0510603 instrumental and observational effects. and 2022YFF0503402), National Natural Science Foundation Among various observational effects, the PSF is particularly of China (NSFC, grant No 12141302), and the China Manned important for point sources, as it redistributes the flux across Space Project with No. CMS-CSST-2025-A07. J.G. acknowlmultiple adjacent spaxels, leading to spatial broadening and edges support from the National Astronomical Observatories dilution of the central intensity. In future versions of GEHONG, of the Chinese Academy of Sciences (No. E4ZR0510), the we plan to implement a simplified PSF convolution option, Beijing Municipal Natural Science Foundation (No. 1242032), such as applying a Gaussian kernel, to enable approximate the National Key Research and Development Program of modeling of spatial blurring effects when needed. China (No. 2023YFA1607904), and the Youth Innovation Promotion Association of the Chinese Academy of Sciences 6. Summary (No. 2022056). IFS has revolutionized the study of galaxies by providing 3D datacubes that simultaneously capture spectral and spatial Appendix information. The upcoming CSST will be equipped with a Usage of GEHONG high-spatial-resolution Integral Field Spectrograph (CSST- The GEHONG package is publicly available at https://csst- IFS) to enable detailed investigations of the internal ifs-gehong.readthedocs.io/. Users can install the package via structures of galaxies. To support scientific preparation and pip using the following command:

pip install csst-ifs-gehong Finally, the spectrum of a single star shown in Figure 4 can be generated using: Comprehensive documentation and detailed usage instructions are provided on the website. For the convenience of # Load the template for a single star readers, we also present the example codes used to generate star_temp = spec1d.SingleStarTemplate(conf) the mock cases below, as shown in the figures throughout this # Generate the single stellar spectrum paper. The following code example is based on version 3.1.0 star = spec1d.SingleStar(conf, star_temp, mag = 15, teff = 8000, feh = -0.1, logg = 3, vel = 800, ebv = 0.1) of GEHONG.

A.1. spec1d Module This section provides example codes for generating the A.2. map2d Module mock spectra presented in the figures throughout the paper using the spec1d module. The 2D maps in Figure 5 are mocked using the following To reproduce the ionized gas emission lines shown in codes: Figure 2, the following codes can be used:

Initialize the surface brightness map

sbmap = map2d.Map2d(config) # Set the configuration of data format # Mocking the map of surface brightness conf = config.config() sbmap.sersic_map(mag = 15.0, reff = 4, n = 1.0, ellip = 0.6, theta = 30) # Load the H II region emission line template # Initialize the velocity map gas_tem = spec1d.EmissionLineTemplate(conf, model = "hii") velmap = map2d.Map2d(config) # Generate the ionized gas emission lines of an H II region # Mocking the map of velocity gas = spec1d.H II_Region(conf, gas_tem, halpha = 500, logz = -0.2, velmap.tanh_map(vmax = 160, rt = 2.0, ellip = 0.8, theta = 0) vel = 30000, vdisp = 150, ebv = 0.1) # Initialize the stellar age map agemap = map2d.Map2d(config) # Mocking the map of stellar age The continuum of the stellar population, also shown in agemap.gred_map(aeff = 9.5, reff = 6, gred = -0.2, ellip = 0.4, theta = 45) Figure 2, can be generated as follows:

Load the stellar population templates

stellar_tem = spec1d.StellarContinuumTemplate(conf) # Generate the stellar population continuum ORCID iDs stellar = spec1d.StellarContinuum (conf, stellar_tem, mag = 17, sfh = 2, ceh = -0.3, Shuai Fengaa https://orcid.org/0000-0002-9767-9237 vel = 30000, vdisp = 150, ebv = 0.1) Shiyin Shenaa https://orcid.org/0000-0002-3073-5871 Renhao Yeaa https://orcid.org/0000-0002-2339-5581 Jianjun Chenaa https://orcid.org/0000-0003-4525-1287 The four components of the AGN spectrum illustrated in Xuejie Daiaa https://orcid.org/0000-0003-0948-4139 Figure 3 can be mocked separately using the following codes: Junqiang Geaa https://orcid.org/0000-0002-1971-5458 Lin Linaa https://orcid.org/0000-0003-1138-8146 # Load the emission line template for the narrow-line region Jiafeng Luaa https://orcid.org/0000-0002-8817-4587 nlr_temp = spec1d.EmissionLineTemplate(conf, model = "nlr") Zhengyi Shaoaa https://orcid.org/0000-0001-8611-2465 # Generate the power-law continuum spectrum Jun Yinaa https://orcid.org/0000-0002-4499-1956 pl = spec1d.AGN_Powerlaw(conf, m5100 = 18, alpha = -1.5, vel = 30000, ebv = 0.1) # Generate the iron emission line spectrum References fe = spec1d.AGN_FeII Andersen, D. R., & Bershady, M. A. 2013, ApJ, 768, 41 (conf, hbeta_broad=800.0, r4570 = 0.4, ebv = 0.1, vel = 30000) Bacon, R., Accardo, M., Adjali, L., et al. 2010, SPIE, 7735, 773508 # Generate the broad-line region spectrum Belfiore, F., Maiolino, R., Maraston, C., et al. 2016, MNRAS, 461, 3111 blr = spec1d.AGN_BLR Belfiore, F., Maiolino, R., Tremonti, C., et al. 2017, MNRAS, 469, 151 (conf, hbeta_flux=800, hbeta_fwhm = 5000.0, vel = 30000, ebv = 0.1) Böker, T., Arribas, S., Lützgendorf, N., et al. 2022, A&A, 661, A82 # Generate the narrow-line region spectrum Bottrell, C., & Hani, M. H. 2022, MNRAS, 514, 2821 nlr = spec1d.AGN_NLR(conf, nlr_temp, halpha = 500, logz = -Bundy, K., Bershady, M. A., Law, D. R., et al. 2015, ApJ, 798, 7 0.3, vel = 30000, Byler, N., Dalcanton, J. J., Conroy, C., & Johnson, B. D. 2017, ApJ, 840, 44 Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, ApJ, 533, 682 vdisp = 400, ebv = 0.1) Cano-Díaz, M., Maiolino, R., Marconi, A., et al. 2012, A&A, 537, L8

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