The Physical Characteristics of Interstellar Medium in NGC 3665 with Herschel Observations

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Abstract

We present the analysis of the physical properties of the interstellar medium in the nearby early-type galaxy NGC 3665, based on the far-infrared photometric and spectroscopic data as observed by the Herschel Space Observatory. The fit to the spectral energy distribution reveals a high dust content in the galaxy, with a dust-to-stellar mass ratio of $M_{\text{dust}}/M_*=1.1 \times 10^{-4}$ that is nearly three times larger than the mean value of local S0+Sa galaxies. For the ionized regions (H II regions), the electron density ($n_e$) is around $49.5 \pm 11.9$ cm$^{-3}$ based on the [N II] 122 $\mu$m/[N II] 205 $\mu$m ratio. For the photodissociation regions, the heating efficiency ranges from $1.26 \times 10^{-3}$ to $1.37 \times 10^{-3}$ based on the ([C II]+[O I] 63 $\mu$m)/$L_{\text{TIR}}$, which is slightly lower than other local galaxies; the hydrogen nucleus density and the strength of the far-UV radiation field are $n_e \sim 10^4$ cm$^{-3}$ and $G_0 \sim 10^{-0.28}$, respectively. The above results are consistent with the presence of weak active nuclei and a low level of star-forming activity in NGC 3665. Our results give strong support to the “morphological quenching” scenario, where a compact, massive bulge can stabilize the amount of cool gas against star formation.

Key words: galaxies: elliptical and lenticular, cD – galaxies: individual (NGC 3665) – galaxies: ISM – infrared: ISM – ISM: lines and bands

1. Introduction

The interstellar medium (ISM) plays a crucial role in the galaxy formation and evolution. It is the primary reservoir for star formation. The mutual interaction between the ISM and stars determines the rates of both gaseous depletion and star formation in the galaxy. The ISM contains several main components: ionized gas, neutral gas, cold molecular clouds, and dust grains. When molecular clouds collapse under their own gravity to form stars, the gravity is required to overcome the random motion pressure, which requires the interstellar gas to be cooled down sufficiently. Neutral and ionized gas can be heated up by the photoelectric process (PE; Tielens & Hollenbach 1985) and cooled via collisional excitation of C$^+$, O, N$^+$, and other elements. The atomic fine-structure emission lines in the far-infrared (FIR), such as [N II] 122 and 205 $\mu$m, [C II] 158 $\mu$m, [O I] 63 $\mu$m, and [C I] 370 $\mu$m, are very important coolants, which play a crucial role in the thermal balance in the H II regions and photodissociation regions (PDRs), and can serve as critical diagnostic tools for studying the physical properties of the ISM (e.g., Kaufman et al. 1999).

Among these fine-structure lines, [C II] 158 $\mu$m is the brightest and the dominant FIR cooling line, typically accounting for 0.1%–1% of the total FIR luminosity (Stacey et al. 1991; Malhotra et al. 2001; Díaz-Santos et al. 2013; Sargsyan et al. 2014). The ionization potential of carbon is 11.26 eV; thus, the [C II] line can be a tracer of both ionized and neutral gas. The [O I] emission originates in the PDRs since the ionization potential of oxygen is just above 13.6 eV, whereas the [N II] line exclusively arises from the ionized gas, as nitrogen has an ionization potential of 14.5 eV. As shown in previous studies (Zhao et al. 2013, 2016a; Sargsyan et al. 2014), both the [N II] 205 $\mu$m and [C II] 158 $\mu$m lines can serve as useful indicators of star formation rate (SFR).

Based on the critical densities of collisional excitations for [N II] 122 and 205 $\mu$m, ~293 and 44 cm$^{-3}$ at the electron temperature of 8000 K, respectively, the [N II] 122/[N II] 205 ratio is a sensitive probe of the electron density ($10^{-3} \lesssim n_e \lesssim 300$ cm$^{-3}$) of ionized gas, which can be further used to estimate the fraction of [C II] 158 $\mu$m originating from ionized gas (Oberst et al. 2006, 2011).

Based on Infrared Space Observatory observations, Malhotra et al. (2000) investigated the physical properties of gas and dust in four elliptical/S0 galaxies and proposed that a softer radiation field might result in lower [C II]/$F_{\text{FIR}}$ ratios than those of normal star-forming galaxies by a factor of 2–5. With data from Herschel Space Observatory (hereafter Herschel; Pilbratt et al. 2010), Lapham et al. (2017) presented spectroscopic observations of the FIR emission lines in 20 nearby elliptical/S0 galaxies and found that the average [C II]/$F_{\text{FIR}}$ ratio is slightly lower than that of spiral galaxies, and [C II] luminosity can serve as a good SFR tracer for both early-type galaxies (ETGs) and spirals. Furthermore, Lapham et al. (2017) showed that the fraction of [C II] emission arising from ionized gas is similar in ETGs (63.5%) and normal spirals (53.0%).

In this work, we investigate the ISM properties of a nearby ETG, NGC 3665. In general, ETGs in the local universe contain very little cool gas and/or dust. Many studies focused on the mechanisms of star formation suppression for nearby ETGs, such as removing cool gas (Di Matteo et al. 2005; Hopkins et al. 2006), suppressing gas infall and cooling...
...their implications in Section 3, including the classification of nuclear activity, SED fitting, the SFR, the ionized gas contribution to the [C II] 158 μm emission, the photoelectric heating efficiency of the interstellar gas, and some derived values using the PDR model. Then, we compare our results with respect to the star formation and gas to the previous works and discuss the possible mechanisms to suppress star formation in NGC 3665 in Section 4. The conclusions for this work are summarized in Section 5.

2. Observations and Data Reduction

2.1. Herschel PACS and SPIRE Photometry

NGC 3665 was observed with Herschel PACS and SPIRE in two open time projects, GT2_mbaes_2 (PI: M. Baes) and OT1_lyoung_1 (PI: L. Young), respectively. We performed aperture photometry with the public Level 2 map products, which were downloaded from the Herschel Science Archive. To match the 36′ resolution of the 500 μm image, we convolved other band images with the kernels provided in Gordon et al. (2008). We adopted an aperture of 40′′ radius around the source and determined the sky values within a 60′′–90′′ annulus surrounding the target galaxy. The photometric errors on the source were given by the standard deviation of 15 annuli between 60′′ and 90′′ around the source, as well as the 5% uncertainty of the fiducial stellar models in the PACS photometry and the confusion noise in the SPIRE photometry (Herschel Observers’ Manual, v.5.0.3, 2014). We then applied the corresponding color and aperture corrections to these fluxes. The final photometric fluxes are given in Table 1.

2.2. Herschel PACS and SPIRE Spectroscopy

The Herschel FIR spectroscopic observations of NGC 3665 were performed by the program OT1_lyoung_1 (PI: L. Young; Lapham et al. 2017), with a total exposure time of 60.7 hr of Herschel. We focused on the [N II] 122 and 205 μm, [C I] 370 μm, [C II] 158 μm, and [O I] 63 μm fine-structure lines observed with the PACS (better than 12′′) and SPIRE (∼17′′ and ∼36′′) instruments.

2.2.1. PACS Flux Measurement

The PACS integral-field spectrometer covers the 51–220 μm range with a spectral resolution of ∼75–300 km s⁻¹, which is composed of 5 × 5 squared spatial pixels (spaxels), each with a size of 9.7′. It covers a total projected field of view (FOV) of 47′′ × 47′′. The angular resolutions are 9.7′′ at ∼63 μm, 10.0′′ at ∼122 μm, and 11.6′′ at ∼158 μm. For NGC 3665, the [O I] 63 μm, [N II] 122 μm, and [C II] 158 μm data are composed of observations acquired in the mapping mode. The Level 2 data with standard rebinned cubes, observed with line range spectroscopy mode and reduced with the Herschel Interactive Processing Environment (HIPE; Ott 2010) version 14.2, were downloaded directly from the Herschel Science Archive. The spectrometer effective spectral resolutions are about 86 km s⁻¹ (the third grating order), 290 km s⁻¹ (the first grating order), and 238 km s⁻¹ (the first grating order) for [O I] 63 μm, [N II] 122 μm, and [C II] 158 μm, respectively. The basic observational information for each line is summarized in Table 2.

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**Table 1**

| Band (μm) | Beam FWHM Size (arcsec) | Pixel Size (arcsec) | Color Correction | Aperture Correction | Flux (Jy) |
|-----------|-------------------------|--------------------|------------------|---------------------|---------|
| 100       | 7.7                     | 1.6                | 1.000            | 1.271               | 6.68 ± 0.34 |
| 160       | 12                      | 3.2                | 1.004            | 1.271               | 7.27 ± 0.37 |
| 250       | 18.1                    | 6.0                | 0.9121           | 1.256               | 2.84 ± 0.45 |
| 350       | 24.9                    | 10.0               | 0.9161           | 1.256               | 1.09 ± 0.12 |
| 500       | 36.4                    | 14.0               | 0.9005           | 1.256               | 0.35 ± 0.10 |

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7. [http://herschel.esac.esa.int/Science_Archive.shtml](http://herschel.esac.esa.int/Science_Archive.shtml)

8. [http://herschel.esac.esa.int/Docs/Herschel/html/Observatory.html](http://herschel.esac.esa.int/Docs/Herschel/html/Observatory.html)
Following Farrah et al. (2013), we co-added the spectra of the central 9 spaxels to measure the line fluxes, due to the fact that the line-emitting regions in NGC 3665 are not confined in the central spaxel according to its 100 μm continuum emission. Then we fitted the observed spectrum with two Gaussian functions (for the line) plus a linear component (for the continuum). We fitted the observed spectrum with two Gaussian functions (for the line) plus a linear component (for the continuum).

### Table 2

| Line        | λ  (μm) | ObsID       | Obs. Date   | Spec. Resolution (km s⁻¹) | Angular Resolution (arcsec) | Flux (10⁻¹⁷ W m⁻²) | FWHM (km s⁻¹) |
|-------------|---------|-------------|-------------|---------------------------|-----------------------------|--------------------|---------------|
| [O I]       | 63.18   | 134223367   | 2011 Jun 30 | ~86                       | ~9.4                        | <2.48              | ...           |
| [N II]      | 121.90  | 1342234055  | 2011 Dec 11 | ~290                      | ~10                         | 14.09 ± 1.98      | 279, 221      |
| [C II]      | 157.74  | 1342234055  | 2011 Dec 11 | ~238                      | ~11.5                       | 48.09 ± 0.84      | 248, 251      |
| [N II]      | 205.18  | 1342247121  | 2012 Jun 18 | ~297                      | ~17                         | 7.24 ± 0.10       | 568           |
| [C II]      | 370.42  | 1342247121  | 2012 Jun 18 | ~536                      | ~36                         | 0.40 ± 0.05       | ...           |

Note. Column (1): atomic fine-structure line. Column (2): wavelength. Column (3): observation ID. Column (4): observation date. Columns (5) and (6): spectral resolution and angular resolution from the PACS Observer’s Manual and SPIRE Handbook. Column (7): measured fluxes of each atomic fine-structure line for NGC 3665. Column (8): intrinsic line width.

Figure 1. [C II] 158 μm, [N II] 122 μm, and [O I] 63 μm spectra combined within the central 3 × 3 spaxels. In the left two panels, the top and bottom black lines show observed spectra and emission lines with two Gaussian components fitted in red, respectively. The continuum emission was fitted by a first-order polynomial in blue. The right panel shows observed spectra of [O I] 63 μm.

Figure 2. [C II] 158 μm and [N II] 122 μm integrated intensity maps (color scale), overlaid with contours of CO (1−0) integrated intensity (moment 0) from CARMA. We have used the 3σ cut to highlight the robust detections. Contour levels are 2.5%, 16%, 50%, and 84% of the peak, while the peak flux is 24.04 Jy beam⁻¹ km s⁻¹. The color table on the right of each panel provides the integrated flux scale of [C II] 158 μm and [N II] 122 μm, respectively, with units of 10⁻¹⁷ W m⁻². The synthesized beams of Herschel and CARMA are shown in the lower left corner with the black open circle and gray filled circle, respectively. North is up, and east is to the left.
continuum), as shown in Figure 1. The uncertainty of the integrated flux was calculated according to the rms of the continuum. A point-source aperture correction (Balog et al. 2014) was applied to derive the final flux. The intrinsic line width (\(\sigma_{\text{true}}\)) was obtained using \(\sigma_{\text{true}} = \sqrt{\sigma_{\text{obs}}^2 - \sigma_{\text{inst}}^2}\), where \(\sigma_{\text{obs}}\) and \(\sigma_{\text{inst}}\) are the observed line width and instrumental spectral resolution, respectively. The [O I] 63 \(\mu m\) is not detected, and thus we calculated its upper limit using 3\(\sigma\) times the instrumental spectral resolution at the considered wavelength. The line fluxes are given in Table 2. In Figure 2, we show the [C II] 158 \(\mu m\) and [N II] 122 \(\mu m\) integrated emission maps, overlaid with the \(^{12}\)CO (J = 1–0) moment 0 contours from the CARMA ATLAS3D survey (Alatalo et al. 2013). The maps are created by projecting the rasters onto a common, regular spatial grid with 1″86 and 1″63 pixel sizes, respectively, clearly showing that the neutral and ionized gas has extended structures and follows the CO (1–0) gas disk. Both of these two cooling lines are strongest at the center and weaker outward, suggesting a mount of [C II] 158 \(\mu m\) lines generated from ionized gas, which emits the [N II] 122 \(\mu m\). The offset on the nucleus in each panel of [C II] 158 \(\mu m\) and [N II] 122 \(\mu m\) lines compared with the CO (1–0) contour is smaller than 2″ and within the beam size. Since the nondetection of [O I] 63 \(\mu m\) and the [N II] 122 \(\mu m\) emission marginally resolved, we tried but failed to perform radial decomposition. Thus, we only concentrated on the analysis of the integrated properties of NGC 3665.

2.2.2. SPIRE Flux Measurement

The SPIRE Fourier-Transform Spectrometer consists of two bolometer detector arrays, the SPIRE Short Wavelength Spectrometer Array (SSW), and the SPIRE Long Wavelength Spectrometer Array (SLW), covering overlapping bands of 191–318 \(\mu m\) and 294–671 \(\mu m\), respectively. The observations were conducted in the single pointing mode with a high spectral resolution of 0.04 cm\(^{-1}\) (or 1.2 GHz in frequency space). We used the Level 2 data products, which were reduced using the standard pipeline provided by the HIPE version 14.0, along with the SPIRE calibration version 14.2.

To obtain the integrated fluxes of [C I] and [N II] 205 \(\mu m\) lines, we followed the method in Lu et al. (2017). For the [C I] 370 \(\mu m\) line, we adopted a pure Sinc function, as (1) this line is only partially resolved given the large instrumental resolution (~540 km s\(^{-1}\)) at 370 \(\mu m\), and (2) the signal-to-noise ratio (S/N) is not high enough to use a Sinc-convolved Gauss function. For the [N II] 205 \(\mu m\) line, we adopted a Sinc-convolved Gauss function, as the velocity resolution at ~205 \(\mu m\) is about 300 km s\(^{-1}\). We also used FTLinefitter\(^9\) (FTFitter; in version 1.9) to fit the observed spectra and obtained similar results. Table 2 gives the line fluxes of [N II] 205 \(\mu m\) and [C I] 370 \(\mu m\).

The SPIRE beam size at 205 \(\mu m\) is ~17″ and thus might not cover the total emission of the [N II] line. To check this, we used the correlation between the ratio of [N II] 205 emission to total infrared luminosity \(L_{\text{IR}}(205 \mu m)/L_{\text{TIR}}\) (see Section 3.2 for the calculation of \(L_{\text{TIR}}\) used here) and FIR color (Zhao et al. 2016a): \[\log(L_{\text{IR}}(205 \mu m)/L_{\text{TIR}}) = -3.83 - 1.26x - 1.86x^2 - 0.90x^3\], where \(x = \log(f_{70}/f_{60})\), and \(f_{70}\) and \(f_{60}\) represent the flux densities at 70 and 160 \(\mu m\), respectively. We obtained a total [N II] 205 emission of ~6.12 × 10\(^{-17}\) W m\(^{-2}\), consistent with the measured value within the uncertainties. Furthermore, the [N II] flux is \((7.29 ± 0.14) \times 10^{-17}\) W m\(^{-2}\) after calibrating with the Semi Extended Correction Tool in Lapham et al. (2017). Therefore, the distribution of [N II] 205 \(\mu m\) emission should not deviate much from a point-like source relative to the 17″ beam.

2.3. Optical Spectroscopy

The optical spectroscopic observations were carried out with the 3.5 m telescope at Calar Alto Observatory (CAHA,\(^10\) Almería, Spain) on 2017 May 26. We used the PPAK integral-field unit (IFU; Verheijen et al. 2004) on the Potsdam Multi-Aperture Spectrometer (Roth et al. 2005) instrument, containing 382 fibers each with a 2″7 diameter and a hexagonal FOV of 74″ × 64″ (Kelz et al. 2006). The V500 grating, which has a spectral resolution (FWHM) of 6 A and wavelength coverage of 3745–7500 A, was adopted. A three-pointing dithering scheme was used with an exposure time of 900 s each. The typical airmass was ~1.1. Raw spectroscopic data were reduced with the RGB reduction pipeline version 0.2, including bias subtraction, flat-field correction, cosmic-ray removal, atmospheric extinction correction, and wavelength and flux calibration. The wavelength calibration was performed based on Hg/He lamp exposures at the beginning of the observations every time. For the following analysis, we only focus on the central 3″ × 3″ (9 spaxels).

To obtain the emission-line fluxes, we followed the method of Tremonti et al. (2004) and Brinchmann et al. (2004) to model the stellar continuum with templates, which are generated using the popular synthesis code of Bruzual & Charlot (2003, BC03). The template spectra are composed of 10 different ages (0.005, 0.025, 0.1, 0.2, 0.6, 0.9, 1.4, 2.5, 5, and 10 Gyr) and four metallicities (0.004, 0.008, 0.017, and 0.05). For each metallicity, we performed a non-negative least-squares fit to obtain the best-fitting model spectrum using the 10 single-age populations, with the internal dust attenuation model of Charlot & Fall (2000). During the fitting process, each template is convolved with a stellar velocity dispersion from 0 to 200 km s\(^{-1}\) by a step size of 5 km s\(^{-1}\). After subtracting the best-fitting stellar continuum model, we obtained the pure nebular emission line spectrum and fitted each line with one Gaussian component, including H/β, H/α, [O III] λ5007, and [N II] λ6584 lines.

3. Results and Discussion

3.1. Spectral Classification

To identify the power source of the emission lines, we adopted the well-known BPT diagnostic diagram (Baldwin et al. 1981; Veilleux & Osterbrock 1987). Here we only focus on the central 3″ × 3″ region (the IFU data will be fully used in the following paper for a large sample of S0 galaxies) in NGC 3665. In Figure 3, we plotted [N II] λ6584/Hα versus [O III] λ5007/H/β flux ratios with S/N > 3 for all four emission lines. The red solid and dashed lines mark the criteria to separate active galactic nuclei (AGNs) from star-forming galaxies according to Kewley et al. (2001) and Kauffmann et al. (2003), respectively, with composite systems located in between these two lines. The horizontal blue line adopted from Kauffmann et al. (2003) is used to divide galaxies into Seyfert galaxies and LINERs. Green circles represent

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\(^9\) http://www.astro.leidenuniv.nl/\~{}naylor/index.php?page=ftfitter

\(^10\) http://www.caha.es/
individual spaxels (1″ × 1″), whereas the red star shows the entire 3″ × 3″ region. As shown in Figure 3, all of the observed points lie in the composite region, suggesting that the central region of NGC 3665 is a mixture of star formation and a weak AGN and is consistent with Ho et al. (1997). For the central 3″ × 3″ region, the equivalent width of Hα (W_Hα) is ~3.82 Å, and log(N[II]/Hα) is about −0.21, which are also consistent with the identification of weak AGNs (i.e., log([NII]/Hα) > −0.4) and W_Hα between 3 and 6 Å in the W_Hα versus [NII]/Hα (WHAN) diagram (Cid Fernandes et al. 2011). Our results are consistent with Nyland et al. (2016), who detected two extended radio jets on scales of kiloparsecs in NGC 3665. Using the observed ratio of F_Hα/F_Hβ, we can estimate the nebular extinction, A_v,nbular (Cardelli et al. 1989), assuming an unreddened I_Hα/I_Hβ of 2.86 from Osterbrock (1989), e.g.,

$$A_{v, nbular} = 7.2 \times \log \left( \frac{F_{H\alpha}/F_{H\beta}}{I_{H\alpha}/I_{H\beta}} \right).$$

We obtained that the nebular extinction, A_v,nbular, for NGC 3665 is ~1.3, which is larger than the mean value, 1.06 ± 0.66, of 45 star-forming S0 galaxies (Xiao et al. 2016) from the Sloan Digital Sky Survey (SDSS; Abazajian et al. 2009).

Here we roughly calculate the surface density of the SFR in the central 3″ × 3″ region, Σ_SFR, without considering the effect of weak AGNs. Using the Kennicutt (1998b) relation with extinction-corrected H α luminosity,

$$SFR (M_\odot yr^{-1}) = 7.9 \times 10^{-42} L(H\alpha) (\text{erg s}^{-1}),$$

we derive log Σ_SFR ∼ −0.78 M_\odot yr^{-1} kpc^{-2}, which is lower than the mean value, −0.48 M_\odot yr^{-1} kpc^{-2}, of 45 star-forming S0 galaxies with the same method (Xiao et al. 2016). Since the [NII] 122 μm emission is the strongest in the center (see Figure 2), suggesting a similar distribution of H II regions (Zhao et al. 2016a), we conclude that the star formation is concentrated in the galactic center and the rate is low.

### 3.2. SED Fitting

To better understand the infrared properties of NGC 3665, such as the total infrared luminosity (L_TIR: 8–1000 μm as defined in Sanders & Mirabel 1996), dust temperature (T_dust), and dust mass (M_dust), we used the code of Multi-wavelength Analysis of Galaxy Physical Properties11 (MAGPHYS; da Cunha et al. 2008) to fit the observed SED of NGC 3665. Besides the Herschel PACS and SPIRE photometric results, we also compiled UV to FIR photometry from Galaxy Evolution Explorer (GALEX; Loubser & Sánchez-Blázquez 2011), SDSS (Adelman-McCarthy et al. 2008), Two Micron All Sky Survey (2MASS; Jarrett et al. 2000), and Infrared Astronomical Satellite (IRAS; Moshir et al. 1990) catalogs. The measured fluxes are listed in Table 3.

MAGPHYS is a simple model to interpret in a consistent way the emission from galaxies at UV, optical, and IR wavelengths in terms of their star formation histories and dust content, using a Bayesian fitting method. The library of model galaxy spectra is composed of two types of binary files: the “optical models” tracing the emission from stellar populations in galaxies, calculated using BC03 with the initial mass function from Chabrier (2003) and the dust attenuation model described in Charlot & Fall (2000); and the “infrared models” tracing the emission from dust, following the approach described in da Cunha et al. (2008). This model relies on the assumption that the total energy is absorbed by dust from two main components (Charlot & Fall 2000), the stellar birth clouds (star-forming regions) and the ambient diffuse ISM, and re-radiated by dust at IR wavelengths via an energy balance argument.

We present the result of SED fitting for NGC 3665 in Figure 4. In the top panel, the black line shows the best model fitting to the observed data (red points), while the blue and red lines represent the unattenuated stellar population spectrum and the dust emission, respectively. The residuals (L_{obs} − L_{mod})/L_{obs} are shown with black squares. As we can see, the modeled spectrum is in good agreement with the observed data points from GALEX 1539 Å to Herschel SPIRE 500 μm.

Table 4 lists the derived parameters from the best-fit SED. The dust-to-stellar mass ratio M_{dust}/M_* of NGC 3665 is about 1.1 × 10^{-4}, which is about 3 times higher than the mean value for 39 S0+S0a galaxies observed with Herschel (Smith et al. 2012). As shown in Alatalo et al. (2013), NGC 3665 has a total molecular gas mass of log M_gas = 9.11 ± 0.01 M_\odot, indicating that the gas-to-dust mass ratio (GDR) is ~182, which is similar to the value of the Milky Way, e.g., ~120 from Li & Draine (2001), ~160 from Zubko et al. (2004), and ~180 from Draine et al. (2007). We also calculated the total infrared luminosity (L_TIR) of NGC 3665, integrated within 8–1000 μm from the SED best-fitting model, to be 10^{10.88±0.02} L_\odot. The error is estimated through performing a Monte Carlo simulation, sampling a series of data points according to a Gaussian distribution with the measured photometric values and errors, and repeating the same fitting procedure for 1000 times using the simulated data sets.

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11 http://www.iap.fr/magphys/magphys/MAGPHYS.html
We also ran another SED fitting model, CIGALE\(^{12}\) (Noll et al. 2009) version 0.11.0, to make a comparison. The derived values of stellar mass and dust luminosity are log\(M_\star = 10.79\) \(M_\odot\) and log\(L_d = 9.97\) \(L_\odot\), respectively, consistent with the results from MAGPHYS. Therefore, we adopted the fitted parameters from MAGPHYS in the following analysis.

\(^{12}\)http://cigale.lam.fr
3.3. Star Formation Rate

To estimate the SFR in NGC 3665, we adopted several different approaches:

1. Using the infrared and \textit{GALEX} FUV luminosity (Dale et al. 2007):

\[
\text{SFR}(M_\odot \text{ yr}^{-1}) = 4.5 \times 10^{-37} L_{\text{TIR}}(\mu\text{m}) \nonumber + 7.1 \times 10^{-37} L_{\nu,1500}(\text{W}) 
\]

where \( L_{\text{TIR}} \) is calculated from integration within 8–1000 \( \mu \text{m} \) from SED fitting (see the Section 3.2). The SFR in NGC 3665 is derived to be \( 1.34 \pm 0.06 M_\odot \text{ yr}^{-1} \).

2. Based only on \( L_{\text{TIR}} \), with the algorithm of Kennicutt (1998b):

\[
\text{SFR}(M_\odot \text{ yr}^{-1}) = 4.5 \times 10^{-44} L_{\text{TIR}}(\text{erg} \text{ s}^{-1}) .
\]

The derived SFR is \( 1.29 \pm 0.06 M_\odot \text{ yr}^{-1} \). As we know, the weak AGN in NGC 3665 might contribute to the IR emission, which leads to an overestimated SFR. However, the results of CITALE suggest that the fractional contribution of AGNs to the dust emission, \( f_{\text{AGN}} \), is less than 0.01; thus, we ignored its contribution to the infrared luminosity.

3. As shown in Zhao et al. (2013, 2016a), the [N II] 205 \( \mu \text{m} \) luminosity \( (L_{\text{N II},205} \mu\text{m}) \) is less affected by emissions from older stars compared to the IR luminosity, but it is also a good indicator of SFR. With the 60-to-100 \( \mu \text{m} \) flux density ratio, \( f_{60}/f_{100} \sim 0.3 \) in NGC 3665, we adopted the relation suitable for the cold FIR color (0.2 \( \leq f_{60}/f_{100} \leq 0.6 \)):

\[
\log \text{SFR}(M_\odot \text{ yr}^{-1}) = -5.99 + \log L_{\text{N II},205}(\text{L}_\odot) .
\]

We calculated SFR to be \( 2.55^{+1.01}_{-1.01} M_\odot \text{ yr}^{-1} \), where the error is estimated from the uncertainty (0.22 dex) associated with the SFR calibrator given in Zhao et al. (2016a).

(4) The [C II] 158 \( \mu \text{m} \) emission can also serve as a useful indicator of SFR (Sargsyan et al. 2014), as

\[
\log \text{SFR}(M_\odot \text{ yr}^{-1}) = \log L_{\text{[C II]}}(\text{L}_\odot) - 7.0,
\]

with a scatter of 0.2 dex. The derived SFR is \( 1.66^{+0.97}_{-0.97} M_\odot \text{ yr}^{-1} \).

Therefore, SFRs from different calibrators are consistent with each other within uncertainties, and we take the averaged value of \( 1.7 M_\odot \text{ yr}^{-1} \) as the final result.

3.4. The Photodissociation Region

3.4.1. [C II] Emission from Ionized Gas

The emission of [C II] originates from both the neutral and ionized gas, due to the low ionization potential (11.26 eV) of atomic carbon. To use the PDR models, in which only the emission from neutral gas has been taken into account, we first need to remove the [C II] emission from ionized gas. Following the method of Oberst et al. (2006, 2011), the contribution of ionized gas can be estimated with the [C II]/[N II] 205 ratio, which is only a function of electron density \( n_e \) in the H II regions after assuming a C/N abundance ratio. \( n_e \) can be estimated with the [N II] 122/205 ratio because of their different critical densities (Oberst et al. 2006; Zhao et al. 2016a). Comparing the observed value (1.95 ± 0.27) with the theoretical curve, we determine \( n_e = 49.5 \pm 11.9 \text{ cm}^{-3} \), which is comparable to those found in ETGs and star-forming galaxies. For instance, Lapham et al. (2017) found \( n_e = 24 \text{ cm}^{-3} \) for 11 nearby ETGs from \textit{Herschel} observations, and Díaz-Santos et al. (2017) found \( n_e \) from 20 to 100 \text{ cm}^{-3}, with a mean value of 45 \text{ cm}^{-3}, for 240 GOALS luminous IR galaxies. In the Milky Way, the average value is measured to be 29 \text{ cm}^{-3} (Goldsmith et al. 2015), and in nearby spiral galaxy NGC 891, \( n_e \) ranges from 1.9 to 80 \text{ cm}^{-3}, with a mean value of 22 \text{ cm}^{-3} (Hughes et al. 2015).

Based on the Lick indices (Fe5015 and Mg b) and single stellar population models, McDermid et al. (2015) derived the stellar metallicity at \( R_e/8 \) (\( \sim 0.87 \text{ kpc} \)) to be \( [\text{Z}/\text{H}] = -0.05 \pm 0.05 \). We calculated gas-phase metallicity based on the [N II] \( \lambda 6584/\lambda 63 
\] line ratio (Kewley & Dopita 2002) for the same central region to be \( \sim 1.0 \text{ Z}_\odot \). Thus, by adopting solar abundances of \( C/\text{H} = 1.4 \times 10^{-4} \) and \( N/\text{H} = 7.9 \times 10^{-5} \) from Savage & Sembach (1996), we further used the derived electron density to predict the [C II]/[N II] 205 ratio in ionized gas and then compared it with the observed values. We find that the fraction of [C II] emission from ionized gas is about 43%. This value appears consistent with the previous results from various sources that the majority of [C II] emission comes from PDRs (Abel et al. 2005; Oberst et al. 2006, 2011; Farrah et al. 2013; Parkin et al. 2014; Hughes et al. 2015; Lapham et al. 2017). After removing the contribution from ionized gas for the [C II] emission, we estimated that the [C II] flux originating from neutral gas is \( (27.6 \pm 0.5) \times 10^{-17} \text{ W m}^{-2} \).
photoelectric effect, which can be traced by emission lines during gas cooling via collisional excitation at the FIR wavelengths. Another portion of UV photons are absorbed by dust grains and re-emit in the infrared, which can be traced by total infrared flux. Therefore, the ratio of ([C II]+[O I]63)/$F_{\text{TIR}}$ is a criterion for diagnosing photoelectric heating efficiency of the interstellar gas (Tielens & Hollenbach 1985).

The total infrared flux, $F_{\text{TIR}}$, is $2.19 \times 10^{-13}$ W m$^{-2}$, and we calculated the ([C II]+[O I]63)/$F_{\text{TIR}}$ ratio in PDRs to range from $1.26 \times 10^{-3}$ to $1.37 \times 10^{-3}$, where the lower and upper limits were obtained by assuming zero and $3\sigma$ fluxes of the [O I] emission, respectively, whereas the typical values of ([C II]+[O I]63)/$F_{\text{TIR}}$ are in the range of $10^{-3}$ to $10^{-2}$, in both ETGs and late-type galaxies (Malhotra et al. 2001; Brauer et al. 2008; Lapham et al. 2017). For other galaxies with spatially resolved observations, the heating efficiency varies between $\sim 2 \times 10^{-3}$ and $10^{-2}$ in the late spiral galaxy NGC 1097 and Seyfert 1 galaxy NGC 4559 (Croxall et al. 2012). Hughes et al. (2015) also found in NGC 891 a ([C II]+[O I] 63)/$F_{\text{TIR}}$ ranging from $\sim 1 \times 10^{-3}$ to $2 \times 10^{-2}$ using Herschel FIR spectroscopic observations. Parkin et al. (2014) showed that the heating efficiency in the disk of Centaurus A ranges from $4 \times 10^{-3}$ to $8 \times 10^{-3}$. In the arm and interarm regions of M51, the average value is up to $\sim 10^{-2}$, and in the nucleus it is decreases to $3 \times 10^{-3}$ (Parkin et al. 2013). Therefore, NGC 3665 is among those sources having the lowest gas heating efficiency.

The low gas heating efficiency in NGC 3665 might be caused by its weak UV radiation field. The gas is mainly photoelectrically heated by the UV photons, while dust can be heated by both optical and UV photons (Malhotra et al. 2000). As shown in Abel et al. (2009), the FIR color is a good indicator of the ionization parameter ($U$) of the ambient UV radiation field. For NGC 3665, $f_{60}/f_{100} \sim 0.3$ indicates a very small $U$ of $\sim 10^{-4}$. Therefore, there is not enough energy for the electrons to collisionally excite the C$^+$ and O to higher levels.

\subsection{3.4.3. The PDR Model}

We compare IR emission line ratios to the PDR model to obtain the physical properties of the PDR regions. Here we adopt the PDR model of Kaufman et al. (1999, 2006), which has been updated based on the original model of Tielens & Hollenbach (1985). These models assume a homogeneous semi-infinite 2D slab of a PDR and solve for the chemistry, thermal balance, and radiation transfer simultaneously. For given gas-phase elemental abundances and grain properties, the model is parameterized by two free parameters: the hydrogen nucleus density, $n$, and the strength of the FUV (6 eV < $E$ < 13.6 eV) radiation field, $G_0$, in units of $1.6 \times 10^{-3}$ erg cm$^{-2}$ s$^{-1}$ from the local Galactic interstellar FUV field (Habing 1968).

We adopt the diagnostic observed line ratios of [C II]/[O I]63 versus ([C II]+[O I]63)/$F_{\text{TIR}}$ as mentioned in Wolfire et al. (1990). Here we make several corrections to the observed quantities following the strategy of Zhao et al. (2016b). The cloud is optically thin to the infrared continuum photon, which contributes to the actual observations from the front and back sides of the cloud (especially when they are illuminated from all sides), while the models only take into account one side emission exposed to the source of UV photons. Therefore, we reduce the observed $F_{\text{TIR}}$ by a factor of 2 as suggested by Kaufman et al. (1999).

\begin{table}[h!]
\centering
\caption{Results from the PDR Model}
\begin{tabular}{lcc}
\hline
Case & $\log n$ (cm$^{-3}$) & $\log G_0$ (1.6 $\times 10^{-3}$ erg cm$^{-2}$ s$^{-1}$) \\
\hline
Uncorrected$^a$ & 3.75 & $-0.25$ \\
Corrected$^b$ & 4.00 & $-0.25$ \\
\hline
\end{tabular}
\end{table}

Notes.
$^a$ The uncorrected values are derived from the best fit, including the observed [C II] only from the neutral gas region, all observed [O I]63 emission, and $F_{\text{TIR}}$.
$^b$ The corrected values contain the [C II] divided by a factor of 1.4 in the neutral gas region and the $F_{\text{TIR}}$ reduced by 2.0.

In the PDR models, the emission line is only considered to originate from neutral gas. As mentioned above, the [C II] emission arises from both neutral and ionized gas; we first need to remove the contribution of [C II] from ionized gas, with the fraction of $\sim 43\%$. Besides, we correct the geometrical effect of PDR models to the observed [C II] emission. The [C II] is marginally optically thick with optical depth $\tau \sim 1$ at the line center (Kaufman et al. 1999); thus, the observed emission comes from the front side and partial back side of the cloud. We adopt the correction factor of 1.4 to divide the observed flux when comparing to the 2D PDR models. More methodology details are described in Zhao et al. (2016b).

The [O I]63 line is optically thick. We observe the emission only from the front side of the cloud, while the other about half of the total [O I]63 emission radiates away from the line of sight. Accordingly, the actual observed [O I]63 flux follows the geometrical assumption of PDR models, without any correction applied. Finally, the equation of ([C II]+[O I]63)/$F_{\text{TIR}}$ after correcting is listed as ([C II]/1.4+[O I]63)/($F_{\text{TIR}}/2.0$), where only the [C II] emission originating from neutral gas is taken into account.

Through a comparison of two observed line ratios to the 2D PDR model, with $\chi^2$ minimization in the web-based Photo Dissociation Region Toolbox (PDRT; Pound & Wolfire 2008),\textsuperscript{13} the derived values of hydrogen volume density, $n$, and the incident FUV radiation field, $G_0$, are listed in Table 5. We also list the best-fitting results derived from uncorrected diagnostic observed line ratios in the PDR region compared to the model. Meanwhile, both results before and after correction are shown in Figure 5. The $G_0$ in NGC 3665 is significantly lower than that found in normal, star-forming, and starburst galaxies, as well as galaxies with strong AGNs (Malhotra et al. 2001; Negishi et al. 2001; Kramer et al. 2005; Oberst et al. 2011; Croxall et al. 2012; Parkin et al. 2013; Zhao et al. 2016b). The low $G_0$ indicates a weak FUV radiation field, which is consistent with our previous analysis.

$F_{\text{TIR}}$ is calculated among the whole galaxy, while [C II] emission tends to concentrate in the center of NGC 3665 (see the Figure 2), along with the [O I]63 emission, which might result in the low $G_0$ after comparing with the PDR model. Here we focus on the central spaxel, with a size of 9.2 $\times$ 9.2, to discuss the physical properties of the ISM. The [C II] and [O I] 63 line fluxes in the central region are measured using the same method as in Section 2.2.1. We calculate the central infrared luminosity of NGC 3665 using Herschel photometry at 100,

\textsuperscript{13} http://dustem.astro.umd.edu/pdrt/
Furthermore, its molecular gas surface density $\Sigma_{\text{gas}}$ of NGC 3665 is ~0.9 dex larger than that of spiral galaxies at the same $\Sigma_{\text{SFR}}$. Furthermore, its molecular gas surface density (2.16 $M_{\odot}$ pc$^{-2}$; Davis et al. 2014) is significantly larger than that of spiral galaxies at a given $\Sigma_{\text{SFR}}$ in the KS plane (Bigiel et al. 2008; Leroy et al. 2008, 2013). Shi et al. (2011, 2018) proposed an extended Schmidt law, invoking the stellar mass to have a secondary role (the first is gas mass) in regulating star formation, as $\Sigma_{\text{SFR}} \propto (\Sigma_{\text{star}} \Sigma_{\text{gas}})^{0.09}$. We also compared NGC 3665 with the extended Schmidt law and found that it has the largest offset to this relation among 20 ETGs and has $\Sigma_{\text{star}} \Sigma_{\text{gas}} \sim 1.6$ dex larger than late-type galaxies at the same $\Sigma_{\text{SFR}}$. Here we have calculated the stellar mass surface density to be $10 \Sigma_{\text{SFR}} = 3.56 M_{\odot}$ pc$^{-2}$ with the same method mentioned in the following as Fang et al. (2013). These results reveal that NGC 3665 has large gas reservoirs but less star formation.

Meanwhile, NGC 3665 is in a low-density environment, with a local galaxy surface density within the radius to the 10th nearest neighbor of $\log \Sigma_{10} = -1.24$ Mpc$^{-2}$, and has been classified as a field galaxy in Cappellari et al. (2011). Young et al. (2011) further explained that the poor environment might induce large CO storage in galaxies by cool gas accretion. We derived the contribution from cold dust to the total dust luminosity ($\Sigma_{\text{dust}}$) to be ~70% from MAGPHYS, and we calculate $f_{\text{CO}}/f_{100} \sim 0.3$ to classify NGC 3665 as a “cold” galaxy as in Zhao et al. (2016a). These results reveal a high cool gas proportion in our source. Among current studies, scenarios proposed to prevent star formation can be roughly divided into three different routines: the cutoff of gas inflow, the removal (or heat) of cool gas in galaxies, and the stabilization of cold gas reservoirs (Martig et al. 2009; Fang et al. 2013; Bluck et al. 2014).

We carried out a 2D bulge–disk decomposition using GALFIT (version 3.0.5; Peng et al. 2002, 2010) and found that the SDSS (Gunn et al. 1998; Aihara et al. 2011) r-band image of NGC 3665 can be fitted very well with one Sérsic

$$L_{\text{TR}} (L_\odot) = (1.379 \pm 0.025)L_{100 \mu m}$$
$$+ (0.058 \pm 0.049)L_{160 \mu m}$$
$$+ (1.150 \pm 0.092)L_{250 \mu m},$$

where $L_{100 \mu m}$, $L_{160 \mu m}$, and $L_{250 \mu m}$ are band luminosities in units of $L_\odot$. The central infrared luminosity is estimated to be $(49.5 \pm 2.3) \times 10^7 L_\odot$. After comparing the two observed line ratios to the PDR model, we derive two physical parameters in the central PDRs of NGC 3665: the hydrogen nucleus density, $n \sim 5.62 \times 10^3$ cm$^{-3}$, and the strength of the FUV radiation field, $G_0 \sim 10^{0.25}$. The $G_0$ in the central region of NGC 3665 is about 3 times larger than that derived from the whole galaxy, while this value is still low enough to indicate a weak FUV radiation field.

4. Abundant Molecular Gas and Suppressed Star Formation

Comparing with the so-called “star-forming main sequence” (stellar mass–SFR relation) at $z \sim 0$ (Elbaz et al. 2007), NGC 3665 lies 0.5 dex lower than the locus of star-forming galaxies at the fixed stellar mass, showing that star formation is suppressed. In Davis et al. (2014), NGC 3665 has $\log \Sigma_{\text{SFR}}$ down to $-2.15 M_\odot$ yr$^{-1}$ kpc$^{-2}$ and shows the largest deviation from the KS relation among 32 CO-detected ATLAS3D ETGs. The gas (atomic+molecular) surface density ($\Sigma_{\text{gas}}$) of NGC 3665 is ~0.9 dex larger than that of spiral galaxies at the same $\Sigma_{\text{SFR}}$. Furthermore, its molecular gas surface density (2.16 $M_\odot$ pc$^{-2}$; Davis et al. 2014) is significantly larger than that of spiral galaxies at a given $\Sigma_{\text{SFR}}$ in the KS plane (Bigiel et al. 2008; Leroy et al. 2008, 2013). Shi et al. (2011, 2018) proposed an extended Schmidt law, invoking the stellar mass to have a secondary role (the first is gas mass) in regulating star formation, as $\Sigma_{\text{SFR}} \propto (\Sigma_{\text{star}} \Sigma_{\text{gas}})^{0.09}$. We also compared NGC 3665 with the extended Schmidt law and found that it has the largest offset to this relation among 20 ETGs and has $\Sigma_{\text{star}} \Sigma_{\text{gas}} \sim 1.6$ dex larger than late-type galaxies at the same $\Sigma_{\text{SFR}}$. Here we have calculated the stellar mass surface density to be $10 \Sigma_{\text{SFR}} = 3.56 M_\odot$ pc$^{-2}$ with the same method mentioned in the following as Fang et al. (2013). These results reveal that NGC 3665 has large gas reservoirs but less star formation.

Meanwhile, NGC 3665 is in a low-density environment, with a local galaxy surface density within the radius to the 10th nearest neighbor of $\log \Sigma_{10} = -1.24$ Mpc$^{-2}$, and has been classified as a field galaxy in Cappellari et al. (2011). Young et al. (2011) further explained that the poor environment might induce large CO storage in galaxies by cool gas accretion. We derived the contribution from cold dust to the total dust luminosity ($\Sigma_{\text{dust}}$) to be ~70% from MAGPHYS, and we calculate $f_{\text{CO}}/f_{100} \sim 0.3$ to classify NGC 3665 as a “cold” galaxy as in Zhao et al. (2016a). These results reveal a high cool gas proportion in our source. Among current studies, scenarios proposed to prevent star formation can be roughly divided into three different routines: the cutoff of gas inflow, the removal (or heat) of cool gas in galaxies, and the stabilization of cold gas reservoirs (Martig et al. 2009; Fang et al. 2013; Bluck et al. 2014). We carried out a 2D bulge–disk decomposition using GALFIT (version 3.0.5; Peng et al. 2002, 2010) and found that the SDSS (Gunn et al. 1998; Aihara et al. 2011) r-band image of NGC 3665 can be fitted very well with one Sérsic
component. The fitting results are listed in Table 6 and shown in Figure 6. The Sérsic index is 3.81, showing that NGC 3665 is a typical bulge-dominated galaxy. Fang et al. (2013) found that the stellar mass surface density within 1 kpc, $\Sigma_1$, is a critical indicator of the star formation suppression. We calculate $\Sigma_1$ following Fang’s method. Using the relation between stellar mass-to-$i$-band luminosity ratio and rest-frame $g - i$ color, $\log M/L_i = 1.15 + 0.79 \times (g - i)$, we measure the value of log $\Sigma_1$ to be $\sim$9.79 $M_\odot$ kpc$^{-2}$. This value is about 0.15 dex higher than the best-fit $\Sigma_1$ versus stellar mass relation for green valley and red sequence galaxies at the fixed stellar mass (Figure 4 in Fang et al. 2013), indicating a relatively compact spheroidal stellar component in our source. With such a compact, massive bulge to stabilize cold gas reservoirs, star formation can be suppressed effectively in NGC 3665.

On the other hand, we estimate the Toomre $Q$ parameter to explore whether the molecular gas disk is stable enough to stand up to the gravitational fragmentation, following the criteria of Toomre (1964):

$$Q_{\text{gas}} = \frac{\sigma_{\text{gas}} \kappa}{\pi G \Sigma_{\text{gas}}} > 1.\quad (8)$$

Here $\sigma_{\text{gas}}$ is the molecular gas velocity dispersion, determined to be 12.53 km s$^{-1}$ with the CARMA observations (Onishi et al. 2017), $\kappa$ is the epicyclic frequency adopted of a approximate relation $\kappa \sim \sqrt{2} \ V(R)/R$, $G$ is Newton’s gravitational constant, and $\Sigma_{\text{gas}}$ is the surface density of the gas disk, determined to be $\sim$145 $M_\odot$ pc$^{-2}$. Thus, we derive $Q_{\text{gas}} \sim 2.6$, suggesting a stable molecular gas disk to stand up to large-scale gas self-gravitational collapse.

Besides the effect of a massive bulge, this galaxy has two extended jets on kiloparsec scales (Nylan et al. 2016), which can both heat the halo gas and expel a fraction of the cool gas (AGN “radio-mode” feedback; Croton et al. 2006; Ogle et al. 2007; Nesvadba et al. 2010; Lanz et al. 2016; Smethurst et al. 2016; Combes 2017). In addition, on account of the high stellar mass of 10.79 $M_\odot$, there is another possible mechanism to prevent star formation by shock heating the gas inflow from the halo (Kereš et al. 2005; Dekel & Birnboim 2006; Cappellari 2016). However, with the low percentage of hot gas, these two modes of star formation suppression are unlikely the dominant mechanisms in NGC 3665. The metallicity is $\sim$1.0 $Z_\odot$; thus, we can exclude the effect of the metallicity in decreasing star formation (Shi et al. 2014).

Consequently, the suppression of star formation in NGC 3665 is most possibly caused by its compact, massive bulge through stabilizing cold gas, which enables NGC 3665 to serve as a good observational sample for the stabilization of cold gas reservoirs, and is influenced by the “radio-mode” feedback, as well as the virial shocks. The low rate of star formation and weak AGNs produce a weak UV radiation field (see details in Section 3.4.3); thus, more dust is heated by old stars with inefficient photoelectric heating of the gas. The weak UV radiation field cannot produce much [C II] and [O I]63 emission and leads to somewhat low $([\text{C II}]+[\text{O I}]63)/F_{\text{TIR}}$ in this atypical early-type galaxy.

### 5. Conclusions

We present Herschel FIR photometric and spectroscopic observations of NGC 3665. To better understand the nuclear activity in NGC 3665, we also conducted optical spectroscopic observations. By combining the multiband data from the literature and fitting the observed SED, we obtain the dust luminosity, stellar and dust mass, dust temperature, infrared luminosity, and GDR in NGC 3665. We discuss gas heating and cooling efficiency in the PDR regions and compare observed emission line ratios to the Kaufman et al. (1999, 2006) PDR models to derive the hydrogen nucleus density and the strength of the FUV radiation field. The main results are summarized as follows:

1. From the PACS spectroscopic maps of [C II] 158 $\mu$m and [N II] 122 $\mu$m, we find that both neutral gas and ionized gas have extended structures and follow the CO (1–0)
gas disk distribution. The fluxes are strongest at the center and gradually weaker outward.

2. NGC 3665 has dust-to-stellar mass ratio $M_{\text{dust}}/M_{\text*} \sim 1.1 \times 10^{-4}$, which is nearly 3 times larger than the mean value of local S0+Sa galaxies. The gas-to-dust mass ratio is 182, similar to that in the Milky Way, indicating a large gas reservoir.

3. According to the BPT diagnostic diagram, NGC 3665 contains both star formation and a weak AGN in the central region. We calculated the SFR to be around $1.7 M_{\odot}$ yr$^{-1}$ based on several different methods.

4. The electron density of ionized gas in NGC 3665, based on the [N II] 122/[N II] 205 ratio, is $n_e = 49.5 \pm 11.9$ cm$^{-3}$. The contribution of the ionized gas region to the total [C II] emission is about 43%, which is consistent with previous results that the majority of [C II] emission comes from PDRs.

5. The $(\langle [\text{C II}] + [\text{O III}] \rangle)/F_{\text{TR}}$ line ratio ranges from $1.26 \times 10^{-3}$ to $1.37 \times 10^{-3}$, indicating that NGC 3665 almost has the lowest gas heating efficiency in PDRs among different kinds of galaxies.

6. A comparison between the observed emission line ratios and the theoretical PDR models shows that the hydrogen density $n \sim 10^{3.75}$ cm$^{-3}$ and the strength of the FUV radiation field $G_0 \sim 10^{-0.25}$, indicating a very weak UV radiation field in NGC 3665.

7. After comparing our results with previous works, we find that NGC 3665 has large gas reservoirs but low-level star formation. The suppressed star formation is most possibly caused by its compact, massive bulge through stabilizing cool gas reservoirs.

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