The Big Sibling of AU Mic: A Cold Dust-rich Debris Disk around CP−72 2713 in the βPic Moving Group

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Abstract

Analyzing Spitzer and Herschel archival measurements we identified a debris disk around the young K7/M0 star CP−72 2713. The system belongs to the 24 Myr old β Pic moving group. Our new 1.33 mm continuum observation, obtained with the Atacama Large Millimeter/submillimeter Array 7 m array, revealed an extended dust disk with a peak radius of 140 au, probably tracing the location of the planetesimal belt in the system. The disk is outstandingly large compared to known spatially resolved debris disks and protoplanetary disks around stars of comparable masses. The dynamical excitation of the belt at this radius is found to be reconcilable with planetary stirring, while self-stirring by large planetesimals embedded in the belt can work only if these bodies form very rapidly, e.g., via pebble concentration. By analyzing the spectral energy distribution, we derived a characteristic dust temperature of 43 K and a fractional luminosity of $1.1 \times 10^{-3}$. The latter value is prominently high; we know of only four other similarly dust-rich Kuiper Belt analogs within 40 pc of the Sun.

1. Introduction

Following the dispersal of their gas-rich primordial disks, typically by ∼10 Myr (e.g., Ercolano & Pascucci 2017), young stars are thought to be surrounded by planetesimals not incorporated into planets. Depending on the local level of dynamical excitation, in certain regions of the circumstellar environment, low-velocity collisions between planetesimals can result in mergers, while in more stirred regions, fragmentation can occur (Wyatt 2008). Second-generation debris dust grains, produced in the emerging collisional cascade (Hughes et al. 2018), then make the sufficiently stirred parts of the disk observable through their thermal emission at infrared (IR) and millimeter wavelengths and in optical/near-IR scattered light. Studying the spatial distribution of debris material can thus reveal regions where planetesimals could form but the buildup of planets was halted by some environmental conditions.

Knowledge about the location of dust-producing planetesimal belts in young systems can also allow us to constrain our models on the possible dynamical excitation mechanisms (Mustill & Wyatt 2009), as well as pinpointing how these belts form (Métrá et al. 2018). Further, the last few years have seen the discovery of an increasing number of young debris disks with a detectable amount of gas material (e.g., Moór et al. 2011; Lieman-Sifry et al. 2016). In most cases, this gas is likely second-generation (Kral et al. 2019), originated from erosional processes. It implies the presence of volatile-rich bodies (Kral et al. 2017), thus allowing us to probe the ice abundances of (exo)planetesimals (Kral et al. 2016; Métrà et al. 2017, 2019).

A significant fraction of the known young stars (10–50 Myr) in our neighborhood belong to gravitationally unbound, loose associations of stars called moving groups (Torres et al. 2008). Previous IR observations obtained with space-based telescopes led to the discovery of many debris disks, including some of the most iconic ones (e.g., βPic, AU Mic; Aumann 1985; Mathioudakis & Doyle 1991), around the members of these kinematic assemblages (e.g., Rebull et al. 2008; Zuckerman et al. 2011; Donaldson et al. 2012; Riviere-Marchal et al. 2014; Moór et al. 2016). These studies typically revealed higher excess detection rates in moving groups than in samples of older field stars that contain, on average, less dust as a result of longer collisional evolution of their planetesimal belts. This is particularly noticeable for debris disks around stars with spectral types later than K5, where the majority of the small number of known systems are harbored by moving group members (e.g., Kalas et al. 2004; Low et al. 2005; Olofsson et al. 2018; Sissa et al. 2018; Flaherty et al. 2019; Zuckerman 2019). Though the detection rate for debris disks with late-type hosts is higher in young groups than among field stars, it is probable that the IR excess of several late-type members has remained undetected because their disks are faint due to the low luminosity of the host stars and/or their smaller disk masses, on average.

By carefully inspecting the archives of far-IR observations obtained by the Spitzer Space Telescope and the Herschel Space Observatory, we identified a cold, dust-rich debris disk around a nearby star, CP−72 2713 (36.62 ± 0.03 pc; Bailer-Jones et al. 2018; Gaia Collaboration et al. 2018;
Lindegren et al. 2018). The star is late-type; Torres et al. (2006) derived a spectral type of K7e V from a high-resolution spectrum, while Pecaut & Mamajek (2013) and Gaidos et al. (2014) obtained spectral types of K7e IV and M0, respectively, based on low-resolution spectra. As a member of the ~24 Myr old β Pic moving group (BPMG; Torres et al. 2006; Bell et al. 2015; Gagné et al. 2018; Lee & Song 2018), this disk provides a rare opportunity to study the early evolution of planetesimal belts surrounding late-type stars.

In this paper, we present a detailed analysis of this system using multiwavelength observations. Based on spatially resolved far-IR Herschel/PACS and millimeter Atacama Large Millimeter/submillimeter Array (ALMA) images of the dust emission, we model the structure of the disk and constrain the location of the dust-producing planetesimal belt. Additionally, we carried out ALMA line observations to look for CO molecules in the disk.

2. Observations and Data Reduction

2.1. Spitzer/MIPS

The star CP−72 2713 was observed with the Multiband Imaging Photometer for Spitzer (MIPS; Rieke et al. 2004) on board the Spitzer Space Telescope (Werner et al. 2004) at 24 and 70 μm on 2008 November 23 (PI: P. Plavchan). Photometry at 24 μm was taken from the Spitzer Enhanced Imaging Products (SEIP) catalog. The photometric uncertainty was computed as the quadratic sum of the instrumental noise listed by the catalog and the calibration error of 4% (MIPS Instrument Handbook10). The SEIP catalog does not include data from the 70 μm channel. Therefore, we downloaded the pipeline-reduced basic calibrated data images (version S18.13.0) from the Spitzer Heritage Archive and used MOsicking and Point source Extraction (MOPEX; Makovoz & Marleau 2005) to coadd them and correct for array distortions. For further improvement prior to the coaddition, we applied column mean subtraction and time filtering for the images following Gordon et al. (2007). The final image shows a point source close to the Gaia DR2 position of CP−72 2713 (corrected for proper motion between the epochs of observations). The separation is only 0 ″.09 (ΔR.A. = −1 ″.06 ± 0 ″.07, Δdecl. = −0 ″.84 ± 0 ″.07) and 1 ″.6 (ΔR.A. = −1 ″.35 ± 0 ″.20, Δdecl. = −0 ″.76 ± 0 ″.20) at 100 and 160 μm, respectively. Sánchez-Portal et al. (2014) derived a typical absolute pointing accuracy of 0 ″.9 for the phase of the Herschel mission when our target’s observations were performed. Utilizing large number of PACS mini scan maps of standard stars, Marton et al. (2017) found a median positional difference of 1 ″.5 for the blue PACS detector (70 and 100 μm filters) and 1 ″.7 for the red PACS detector (160 μm). Our measured offsets correspond well to the latter values, implying their instrumental origin.

We measured the source’s flux by placing a 15″ radius aperture on the centroid and a sky annulus between 60″ and 70″. Aperture corrections were taken from the appropriate calibration files. To estimate the uncertainty of the measured flux densities, we placed 16 apertures with radii identical to the source aperture extended, we fitted a grid of simple disk models with the Gaia DR2 position being 1″/4 (ΔR.A. = −1 ″.06 ± 0 ″.07, Δdecl. = −0 ″.84 ± 0 ″.07) and 1 ″.6 (ΔR.A. = −1 ″.35 ± 0 ″.20, Δdecl. = −0 ″.76 ± 0 ″.20) at 100 and 160 μm, respectively. The resulting photometric uncertainty was calculated as a quadratic sum of this and the absolute calibration uncertainty of the PACS detector (7%; Balog et al. 2014). The resulting flux densities are in Table 1.

To evaluate whether the detected source is spatially extended, we fitted a two-dimensional Gaussian model to the images using the mpfit2dpeak IDL procedure (Markwardt 2009). At 100 μm, the best-fit Gaussian has an FWHM of 8″.5 × 5 ″.0 × 8 ″.1 × 5 ″.0, while the FWHM sizes of the point-spread function (PSF) in maps performed with a scan speed of 20″ s−1 (as in our case) are 6″.89 × 6″.69 (PACS Observer’s Manual). This implies that CP−72 2713 is marginally resolved at 100 μm. The fitted Gaussian at 100 μm is consistent with the PSF.

Assuming that the observed emission arises from a circumstellar dust ring, we fitted a grid of simple disk models to the 100 μm image. The models have three free parameters: the radius of the ring (R), the position angle (PA; measured east of north), and the inclination (i; angle of the disk plane with respect to the sky plane). Considering that the observation does not resolve the radial structure, we assumed a Gaussian radial
surface brightness profile that peaks at $R$ and has an FWHM fixed to 0.2$R$. Since at this wavelength, the stellar photosphere is predicted to be $\sim 100 \times$ fainter than the measured flux density (Section 3), we neglected its contribution in our modeling. Disk images constructed in this way were then convolved with a PSF model that we constructed from mini scan map observations of $\alpha$ Boo (ObsID 1342247702/1342247703), processed in the same way as that of our target. The wings of the PACS beam form a characteristic trilobe pattern whose orientation depends on the actual roll angle of the observation. To allow direct comparison, we rotated the image of $\alpha$ Boo to match the telescope’s roll angle at the observation of CP – 72 2713. In order to select the best-fitting model and estimate the uncertainties of the fitted parameters, we used Bayesian inference following Moór et al. (2015). The best-fitting model parameters are $R = 2" \pm 0.6$ (or $99^{+22}_{-26}$ au), $i = 29^{+2}_{-6}$, PA = $153^{+60}_{-64}$°. This model and the residuals are displayed in Figures 1(b)-(c). As Figure 1(c) shows, toward the source, no residuals higher than 3σ were observed. The >3σ residuals at the edge of the displayed image are at an angular separation >15" and may be related to background sources.

### 2.3. Observations with the ALMA 7 m Array

We observed CP – 72 2713 with the ALMA 7 m array in the framework of a Cycle 4 project (2016.2.00200.S; PI: A. Kósplá) that focused on the gas content of young dust-rich debris disks. Our Band 6 observations include two 1.875 GHz wide continuum spectral windows, each with 128 channels centered at 217.0 and 233.5 GHz and two additional windows that were designed to cover the $J = 2$–$1$ rotational lines of $^{12}$CO, $^{13}$CO, and C$^{18}$O. The latter two lines were measured in a single window using a channel width of 428.28 kHz and thereby providing a bandwidth of 1.875 GHz with 4096 channels. In the case of $^{12}$CO, the channel width was set to 122.07 kHz; this band had a total width of 468.8 MHz. Two observations were performed, 1 day apart from each other, on 2017 July 25 and 26. In both cases, nine antennas were involved, providing projected baseline lengths ranging between 8.9 and 44.7 m ($6.7$–$33.6 \lambda$). The obtained data were calibrated and flagged with the ALMA reduction tool Common Astronomy Software Applications (CASA v4.7.2; McMullin et al. 2007) utilizing the pipeline script delivered with the data.

### Continuum emission

We used the tclean task in CASA (v5.6.2; McMullin et al. 2007) to construct the continuum image by applying Briggs weighting with a robustness parameter of 0.5. Since no line was detected (see below), we combined nonflagged data from all spectral windows achieving an rms noise level of 0.28 mJy beam$^{-1}$. The beam size is $7.4 \times 5.5$ with a PA of 6°3. The obtained 1.33 mm continuum image (Figure 1(d)) shows a moderately resolved source around CP – 72 2713 with a peak S/N of 5.7. To determine the source’s flux density and constrain the spatial distribution of emitting dust grains, we used the CASA-based uvmultifit tool (Martí-Vidal et al. 2014) that allows one to fit models to the measured visibilities. Prior to this running, the data weights were recomputed using the statwt task. Similarly to the case of PACS image analysis, we adopted a Gaussian ring model with a fixed FWHM width of 0.2$R$. The obtained best-fit solution has $R = 140 \pm 14$ au ($3.8 \pm 0.4$ au), $i = 46^{\circ} \pm 12^{\circ}$, and PA = $130^{\circ} \pm 16^{\circ}$ and yields a flux density of $3.8 \pm 0.6$ mJy (the quoted uncertainty includes a 10% calibration uncertainty). We used the tclean task to compile images of the best-fit model and the residuals (Figures 1(e)-(f)). No significant residual emission appears in the disk region. The fitted center of the model ring shows an offset of $1^{\circ}3$ from the stellar position ($\Delta R.A. = -0^{\circ}3 \pm 0^{\circ}42$, $\Delta$decl. = $-1^{\circ}22 \pm 0^{\circ}45$). The positional accuracy of an ALMA observation with normal calibration can be estimated as the ratio of the achieved resolution and S/N, i.e., $\sim 0.9$ in our case; thus, the observed offset is not significant. The best-fitting disk parameters derived from the analysis of PACS and ALMA data are summarized in Table 2.

### CO line data

We used CASA to compile the spectral line cubes. After the continuum emission was subtracted from the calibrated visibilities using the uvcontsub task, the imaging was done with the tclean task. In the latter step, we used Briggs weighting with a robustness parameter of 0.5, and the channel width was set to 0.4 km s$^{-1}$ for the $^{12}$CO line and 1.4 km s$^{-1}$ for data of the rarer $^{13}$CO and C$^{18}$O isotopologues. Using the radial velocity data from Table 3, we derived a radial velocity of $+0.4$ km s$^{-1}$ for CP – 72 2713 in the local standard of rest (LSR) frame. We found no significant emission at this velocity (or anywhere else) in the CO data cubes.

In order to estimate an upper limit for the $^{12}$CO (2–1) integrated line flux, we assumed that the possible CO gas is colocated with the dust material in the disk. We defined a disk mask considering those regions in the millimeter continuum image that are adjacent with the maximum brightness and

### Table 1

| $\lambda$ (μm) | Meas. Flux$^a$ (mJy) | Instrument | Photosp. Flux (mJy) | Reference |
|----------------|----------------------|------------|---------------------|-----------|
| 9.00           | 128.1 ± 12.3         | IRC        | 105.2               | Ishihara et al. (2010) |
| 11.56          | 60.0 ± 2.8           | WISE       | 65.0                | Cutri et al. (2013) |
| 22.09          | 18.9 ± 1.5           | WISE       | 18.3                | Cutri et al. (2013) |
| 23.68          | 16.1 ± 0.6           | MIPS       | 16.0                | SEIP      |
| 71.42          | 71.1 ± 5.6           | MIPS       | 1.8                 | This work |
| 100$^b$        | 110.6 ± 9.7          | PACS       | 0.9                 | This work |
| 160            | 103.9 ± 16.9         | PACS       | 0.35                | This work |
| 1330$^b$       | 3.80 ± 0.59          | ALMA       | 0.005               | This work |
| 8820           | 0.096 ± 0.023        | ATCA       | $10.6 \times 10^{-5}$ | Norfolk et al. (2020, in preparation) |

Notes.

$^a$ The quoted flux densities are not color-corrected.

$^b$ The emission is marginally resolved at these wavelengths.
having S/N > 2. Using the obtained mask, we constructed the spectrum and calculated its rms. To consider the correlation between the neighboring channels due to the applied weighting function, this rms was multiplied by $2.667$ (see Matrà et al. 2019, and references therein). Since, based on our results, the bulk of the dust is located at radii $\gtrsim$100 au and the disk inclination is $\lesssim$82° ($3\sigma$ confidence interval), by adopting a stellar mass of 0.71 $M_\odot$ (see Section 3.1), we expect a maximum line width of 5 km s$^{-1}$. Using the corrected rms value and this line width, we derived a $3\sigma$ upper limit of 0.216 Jy km s$^{-1}$ for the $^{12}$CO (2–1) integrated line flux.

Figure 1. Upper panels: (a) PACS 100 $\mu$m image of CP−72 2713, (b) simulated image of the best-fit dust ring model convolved with our PACS PSF (see Section 2.2), and (c) image of residuals. The stellar position is marked with a black star symbol. The gray filled ellipse in the lower left corner represents the size and shape of the PACS PSF (the FWHMs and PA of the ellipse were obtained by fitting a two-dimensional Gaussian to the 100 $\mu$m image of α Boo; see Section 2). In the residual image, contours of $3\times$ the rms noise are also shown. Lower panels: (d) 1.33 mm ALMA continuum image, (e) image of the best-fit model, and (f) residuals image. We note that our modeling was performed in the uv space (Section 2). Panels (e) and (f) display CLEAN images of the best-fit model and residuals after subtracting the model visibilities from the ALMA observations using Briggs weighting with a robustness parameter of 0.5 in the imaging. In panel (f), the dashed and solid contours correspond to the $-3\sigma$ and $+3\sigma$ levels.

Table 2

| Data Set          | PA (deg) | $i$ (deg) | $R$ (au) |
|------------------|----------|-----------|----------|
| PACS 100 $\mu$m  | 153$^{+9}_{-6}$ | 29$^{+2}_{-4}$ | 99$^{+12}_{-8}$ |
| ALMA 1.33 mm     | 130 ± 16 | 46 ± 12   | 140 ± 14 |

Table 3

| Parameter     | Data References |
|---------------|-----------------|
| Distance (pc) | Bailer-Jones et al. (2018) |
| Spectral type | K7Ve            |
| $T_{\text{eff}}$ (K) | This work |
| $L_*$ ($L_\odot$) | 0.18 ± 0.01 |
| $R_*$ ($R_\odot$) | 0.94 ± 0.04 |
| $M_*$ ($M_\odot$) | 0.71$^{+0.03}_{-0.05}$ |
| $L_\odot / L_{\text{bol}}$ | −2.92 |
| $v \sin i_*$ (km s$^{-1}$) | 7.1 ± 0.9$^a$ |
| $P_{\text{rot}}$ (days) | 4.437 |
| $v_{\text{rad}}$ (km s$^{-1}$) | 8.0 ± 0.4$^a$ |

Note.

$^a$ Weighted average of the values reported by the cited papers.
3. Results and Analysis

3.1. Basic Stellar Properties of CP−72 2713

To estimate the basic stellar parameters of CP−72 2713 and provide photospheric flux predictions at IR and millimeter wavelengths, we modeled the stellar photosphere by fitting an ATLAS9 atmosphere model (Castelli & Kurucz 2004) to the photometric data of the star. An active star, CP−72 2713 exhibits variability due to spots (see Figure A1). Using photometric data from the ASAS survey, Kiraga (2012) analyzed 498 and 191 measurements in the V and I bands, respectively. They derived average magnitudes and inferred variability amplitudes of 0.16 and 0.017 mag in the photometric data of the star. An active star, CP (average magnitudes and inferred variability amplitudes of 0.16 and variability due to spots

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The Astronomical Journal, 159:288 (14pp), 2020 June

The star CP−72 2713 has already been observed by TESS (Ricker et al. 2015), providing a very precise, −52 day long photometric data set with a cadence of 2 minutes. The reduction and analysis of these TESS data are described in detail in the Appendix. As further signatures of activity, CP−72 2713 exhibits flares and rotational modulation due to stellar spots in its TESS light curve (Figure A1). Consistent with previous ASAS-based results of 4.456 ± 0.04 (Kiraga 2012) and 4.48 (Messina et al. 2010) days, we obtained a rotation period of P = 4.437 days from a Fourier analysis of our light curve. In addition, we identified 51 flares or groups of flares. We found that the star spent about 936 minutes in a flaring state, which is 1.24% of the time covered by TESS.

3.3. Disk Properties

To construct the spectral energy distribution (SED) of our target at λ > 5 μm, the already reported Spitzer, Herschel, and ALMA data were supplemented by additional space-based mid-IR photometry obtained by the AKARI and Wide-field Infrared Survey Explorer (WISE) satellites. The SED was further supplemented by a recent observation obtained with the ATCA at 9 mm (B. Norfolk et al. 2020, in preparation). The available photometric data, as well as the predicted photospheric flux densities in the specific bands, are given in Table 1. The uncertainty of the predicted photospheric fluxes is estimated to be 5%. The compiled SED, together with the photosphere model, is displayed in Figure 2. While at wavelengths shortward of 25 μm, the measured flux densities are consistent with the predicted photospheric contribution, in the far-IR and millimeter regime, CP−72 2713 exhibits significant excess emission that arises from an extended circumstellar dust disk (Section 2). To estimate the characteristic temperature (T_d) and fractional luminosity (f_d = L_disk / L_bol) of this disk, we fitted the excess emission by a single temperature-modified blackbody model where the emissivity is 1 at wavelengths shorter than λ_0 and varies as (λ/λ_0)^-3 at longer wavelengths. This model accounts for the general observational results that the emission of debris disks exhibits a fall at wavelengths that are large relative to the typical size of the emitting grains. Because of the sparse wavelength coverage, the λ_0 parameter could not be adequately constrained in
our case; thus, in the fitting, we fixed its value to 100 μm. We adopted a Levenberg–Marquardt approach (Markwardt 2009) in searching for the best-fitting model. During the fitting process, we used an iterative way to compute and apply color corrections for our photometric data. As a result, we derived a dust temperature of 43 ± 3 K and a β of 0.05 ± 0.08. The low β value indicates an excess spectrum that is almost identical to a pure blackbody; therefore, changing the λσ parameter has no effect on our results. We note that though most debris disks show considerably steeper millimeter slopes (Gáspár et al. 2012; MacGregor et al. 2016; Marshall et al. 2017), interestingly, the excess SED of AU Mic can also be well reproduced by a blackbody (Matthews et al. 2015). For the fractional luminosity, we obtained \( f_d = 1.1 \times 10^{-3} \).

3.3.1. The Dust Component

Using our ALMA millimeter measurement, we estimated the dust mass in grains of sizes smaller than a few millimeters \((M_d)\). Assuming optically thin dust emission that can be characterized by a single dust temperature, the dust mass is

\[
M_d = \frac{F_v d^2}{B_v(T_d) \kappa_v},
\]

where \(d\) is the distance, \(B_v(T_d)\) is the Planck function at 1.33 mm for the characteristic dust temperature, and \(\kappa_v\) is the dust opacity at the given frequency. Dust particles with sizes >100 μm, whose radiation dominates the emission at this wavelength (Hughes et al. 2018), are thought to behave like blackbodies. At a radial distance of 140 au from CP−72 2713, a star with a luminosity of 0.18 \(L_\odot\) (Section 3.1), the temperature of such grains is ∼15 K. By adopting \(\kappa_v = 2.3 \text{ cm}^2 \text{g}^{-1}\) for the dust opacity (Andrews et al. 2013), Equation (1) provides a dust mass estimate of 0.21 ± 0.03 \(M_\oplus\). The quoted uncertainty accounts for the errors of the measured flux density and the distance of the system. Note, however, that the potential systematic uncertainties of the dust opacity can introduce even a factor of 2−3 difference in the estimate (e.g., Miyake & Nakagawa 1993; Ossenkopf & Henning 1994), and the dust temperature may not be characterized by a single value. These factors were not considered in our error calculations.

3.3.2. The Gas Component

To derive an upper limit for the total CO gas mass using the measured \(^1\text{CO}\) integrated line flux upper limit, we need to estimate the fraction of CO molecules that populate the upper level of the 2−1 rotational transition. Collisions of CO molecules with different gas constituents, radiative processes, and UV pumping (Matrë et al. 2015, 2019) can all affect the population of the rotational levels. Based on the available data, it is difficult to judge the relative importance of these processes in the excitation. In our calculations, we assumed that local thermodynamic equilibrium holds, i.e., that collisions dominate the excitation processes and gas emission is optically thin. Adopting gas temperatures between 10 and 45 K, we derived CO mass upper limits in the range of \((6.8−9.4) \times 10^{-6} M_\oplus\).

3.4. Source Confusion and Contamination Check

So far in our analysis, we have assumed that the observed excess emission solely originates from a circumstellar disk. Knowing the main properties of the source, at this point it is worth assessing the possibility of source confusion, as well as the potential influence of different kinds of contaminations.

First, we examine whether the excess could come from a background galaxy. Based on the recently derived double power-law model of the cumulative number counts of galaxies at millimeter wavelengths (González-López et al. 2020), we estimated a probability of ∼0.006 of the presence of a background galaxy brighter than 3.8 mJy within the primary beam of the ALMA 7 m array. If we consider only the interferometric synthesized beam, this value is reduced to ∼1.1 \times 10^{-4}. Besides the low probability of positional coincidence, there are other strong arguments against this scenario. We measured an angular size of ∼7′′5 for the emitting structure at 1.3 mm. As interferometric observations show, galaxies are compact at (sub)millimeter wavelengths, with a typical size of 0′′3 ± 0′′1 (Franco et al. 2018, and references therein); i.e., they are significantly smaller than our source. The SED of the measured excess emission toward CP−72 2713 peaks at ∼120 μm and has a millimeter spectral index of ∼2. Although the SEDs of local (low-redshift) galaxies peak at a similar wavelength, their millimeter spectral slope is significantly steeper, with typical indices between 3.5 and 4.0 (Casey et al. 2014). Moreover, such low-redshift objects represent only a small fraction of known millimeter galaxies (Casey et al. 2014, and references therein).

Lensed galaxies deserve special attention, since the gravitational lensing effect can magnify distant background sources, thereby increasing both their fluxes and angular sizes. At the spatial resolution we achieved in our ALMA observation, multiple images of lensed galaxies can mimic a source having a more comparable size to that of our target than normal (unlensed) dusty galaxies. However, despite their significant contribution to the bright-end population of galaxies at submillimeter/millimeter wavelengths, lensed dusty star-forming galaxies are rare objects with a sky density of 0.1–0.2 deg−2 (Negrello et al. 2010, 2017; Wardlow et al. 2013; Casey et al. 2014). Thus, the probability that such an object appears within the primary beam of our millimeter observation is less than 4 \times 10^{-5}. The shape of their SEDs also deviates from what we measured toward CP−72 2713: the redshifts of lensed galaxies are typically >2 (Vieira et al. 2013), and their long-wavelength emission peaks at ≥250 μm (Negrello et al. 2017).

Although it is very unlikely that all observed excess is coming from a background galaxy, owing to our coarse spatial resolution, positional coincidence with fainter extragalactic objects cannot be completely ruled out. Recent high spatial resolution millimeter images of several debris disks show compact sources—most likely background galaxies—colocated or located close to the dust ring (Chavez-Dagostino et al. 2016; Booth et al. 2017; Marino et al. 2017; Su et al. 2017; Faramaz et al. 2019). Such objects, if present, can contribute to the measured emission at far-IR and millimeter wavelengths and modify the derived millimeter spectral index of our target. Higher-resolution millimeter observations are needed to explore these possible contaminating sources and assess their role, e.g., in the observed unusually shallow millimeter slope.

In our analysis, the modeling of the stellar contribution to the measured emission was limited to the photospheric fluxes. However, at millimeter wavelengths, low-mass active stars can exhibit nonphotospheric emission (e.g., Lisefau et al. 2015; MacGregor et al. 2015). Recent millimeter ALMA observations of AU Mic revealed a central point source at the star’s position with a flux density ∼6× higher than predicted based
on the pure photospheric model (MacGregor et al. 2013). The observed excess was attributed to either an inner dust belt (MacGregor et al. 2013) or coronal emission from the star itself (Cranmer et al. 2013). In the case of CP–72 2713, the 1σ measurement uncertainty (0.37 mJy) of the 1.33 mm observation is $\sim 80 \times$ higher than the predicted photospheric flux density. Supposing the nonphotospheric contribution at CP–72 2713 is not stronger than in the case of AU Mic (based on their fractional X-ray luminosity (see Kiraga 2012), the coronal activity levels of the two stars are similar), i.e., $\lesssim 6 \times$ the photospheric emission, the measurement uncertainty is significantly higher than the uncertainty of the stellar flux prediction. For shorter periods, however, a higher level of activity cannot be excluded. As was demonstrated in the cases of Proxima Cen and AU Mic, a strong flare can enhance a star’s millimeter flux by orders of magnitudes for a few tens of s (MacGregor et al. 2018; Daley et al. 2019). White et al. (2018) also found significant variability in the 9 mm emission of the young M-type star HD 141569 B throughout its $\sim 1$ hr observation. By examining the obtained ALMA data stream of CP–72 2713, we found no evidence for such flux enhancements. Actually, this meets our expectations: we identified only 51 flare events in the 52 day long TESS light curves (Section 3.2) and found that the star spends only $\sim 1.2\%$ of the time in flare phase in the studied period (in fact, the peaks of the flares, which can substantially contribute to the millimeter emission, cover much less time). Based on all of this, we believe that most of the measured millimeter flux is due to the dust disk.

3.5. Star–disk Alignment

For the projected rotational velocity of the star, Torres et al. (2006) obtained a value of $v \sin i_{\ast} = 7.5 \pm 1.2$ km s$^{-1}$, while Weise et al. (2010) quoted $v \sin i_{\ast} = 6.6 \pm 1.4$ km s$^{-1}$ in their work. Computing the weighted mean of these $v \sin i_{\ast}$ measurements and using the rotational period (in days) and the stellar radius derived above (in solar radii), following Campbell & Garrison (1985) and Greaves et al. (2014), we estimated the inclination of the stellar pole with respect to the line of sight as

$$\sin i_{\ast} = 0.0198 \frac{P_{\ast} \sin i_{\ast}}{R_{\ast}}.$$  

This yields an inclination of $i_{\ast} = 42^\circ \pm 7^\circ$, which is in good agreement with the disk inclination obtained from the analysis of our ALMA data (Section 2.3). This finding coincides well with the conclusions made by Watson et al. (2011), Kennedy et al. (2013), and Greaves et al. (2014); by examining larger debris disk samples, these authors also found no evidence for significant misalignment between the stellar equator and the disk in the studied systems.

4. Discussion

4.1. Evolutionary Status of the Disk

A noteworthy fraction of members in the $\sim 24$ Myr old BPMG exhibit excess emission at IR wavelengths (Rebull et al. 2008; Riviere-Marichalar et al. 2014; Moór et al. 2016). While in most of these systems, the observed excess is likely attributed to thermal emission of tenuous circumstellar debris disks, at least one member of this group, the late-type close binary V4046 Sgr, harbors a long-lived gas-rich protoplanetary disk (e.g., Rosenfeld et al. 2013). Thus, the presence of a protoplanetary disk, even at the age of the BPMG, has previously been seen. Therefore, in the following, we will examine the nature of the CP–72 2713 disk.

Observationally, one of the most conspicuous differences between protoplanetary and debris disks is related to the amount of dust. While protoplanetary disks with their larger dust content are optically thick at most wavelengths, debris disks are optically thin across the spectrum. This is manifested in the fractional luminosities: the threshold between the two classes is typically set to $f_{2} = 0.01$, which is about $10 \times$ higher than that of CP–72 2713. The estimated dust mass of $\sim 0.2 M_{\oplus}$ in our target well matches those of other debris disks (Holland et al. 2017). Recent large surveys of protoplanetary disks implied a positive correlation between disk radius and millimeter continuum luminosity (e.g., Andrews et al. 2010; Trappi et al. 2017; Hendler et al. 2020). The relationship between the effective disk radii ($R_{\text{eff}}$) and the millimeter continuum luminosity ($L_{\text{mm}}$) was studied in five nearby star-forming regions (Ophiuchus, Taurus-Auriga, Chamaeleon I, Lupus, and Upper Sco) by Hendler et al. (2020). In their work, $R_{\text{eff}}$ was defined as the radius that encircles 68% of the continuum emission, while $L_{\text{mm}}$ was the Band 7 flux density scaled to 140 pc. Using our SED model (Section 3.3), we estimated a flux density of 8.4 mJy at 890 $\mu$m for CP–72 2713, which results in $L_{\text{mm}} \sim 6 \times 10^{-4}$ Jy. With its low luminosity and large size of the disk, CP–72 2713 deviates significantly from the observed relationships: protoplanetary disks with $R_{\text{eff}} > 100$ au have at least 2 orders of magnitude higher $L_{\text{mm}}$. The dust properties of our target seem inconsistent with a protoplanetary nature.

The mass of protoplanetary disks is dominated by their gas component, which is no longer present in significant quantities in most debris disks (Wyatt et al. 2015; Kral et al. 2018). We observed no CO emission toward CP–72 2713. The obtained 3σ upper limit on the $^{13}$CO (2–1) line luminosity is about 3 orders of magnitude lower than that of the protoplanetary disk around V4046 Sgr (Rosenfeld et al. 2013). We note that $^{12}$CO in V4046 Sgr is optically thick, suggesting an even higher contrast in the gas mass ratio between the two systems. Even more indicatively, this upper limit also remains six times below the measured $^{12}$CO (2–1) line luminosity of the disk of β Pic, whose gas and dust components are attributed to collisional erosion of larger bodies thus found to be of second generation (Kral et al. 2016; Matrà et al. 2017; Cataldi et al. 2018). Torres et al. (2006) and Gaidos et al. (2014) found the Hα line in emission in CP–72 2713 with measured equivalent widths of 1.9 and 0.84 Å, respectively. Based on the criteria proposed by Barrado y Navascués & Martín (2003), these values can be explained with chromospheric activity and do not indicate ongoing accretion and thus the presence of an inner gas-rich disk.

These findings suggest that our target harbors a gas-poor disk and, together with the results on the dust component, favors the classification of CP–72 2713 as a debris disk.

Nevertheless, with its fractional luminosity of $1.1 \times 10^{-3}$, this disk is considered as a very dust-rich system among debris disks. By comparing this value with that of other cold debris disks with late-type host stars in the BPMG, we can find that it is about $3 \times$ higher than that of the iconic disk of AU Mic ($3.5 \times 10^{-4}$; Matthews et al. 2015) and well matches the
fractional luminosity of the debris disk around AG Tri (10^{-3};
Riviere-Marichalar et al. 2014). Besides CP–72 2713, we
know only four debris systems within 40 pc of the Sun that
have well-established cold dust components and exhibit
fractional luminosities higher than 10^{-2}, namely, β Pic,
HD 61005, TWA 7, and HD 107146.

Despite its large dust content and proximity, the disk of CP
–72 2713 has remained undiscovered for a long time. This is
largely due to the low luminosity of the host star: the system
does not exhibit excess at the mid-IR wavelengths observed by
the WISE satellite, and its far-IR emission falls below the
detection limit of all-sky surveys performed by the IRAS and
AKARI satellites.

### 4.2. Dust Removal Mechanisms

In steady state, the production of dust particles by collisions in
debris disks is balanced by grain removal processes through
radiation and stellar wind forces. In most known debris disks
around main-sequence stars, the stellar radiation pressure plays an
important role in controlling the dust dynamics by driving
particles on more eccentric orbits than those of their parent bodies
and expelling small enough grains from the system (e.g.,
Krivov 2010). In lower-luminosity K- and M-type stars, however,
the radiation pressure is not strong enough to remove grains
(Plavchan et al. 2005; Reidemeister et al. 2011; Schüppler et al.
2015).

Figure 3 shows the ratio of radiation to gravitational force,
\[ \beta_{\text{rad}} = \frac{F_{\text{rad}}}{F_{\text{grav}}} = \frac{M_* \kappa_{\text{rad}}}{16 \pi G M_* c s} \]
for compact spherical dust grains with different \( \rho \) densities and \( s \) sizes in the CP–72 2713 system. We explored four different grain
compositions for which the \( \kappa_{\text{rad}} \) radiation pressure efficiency
was computed by means of Mie theory using the code
developed by Bohren & Huffman (1983). Assuming parent
bodies on a circular orbit, the released grains become unbound
if their \( \beta_{\text{rad}} \) is >0.5. As Figure 3 demonstrates, \( \beta_{\text{rad}} \) remains
below this critical value for each tested dust composition, i.e.,
none of the particles are expelled by the radiation pressure in
the CP–72 2713 system. We note that as an active star, CP
–72 2713 exhibits excess at UV wavelengths and shows strong
coronal X-ray emission (Section 3.2), and during flares, its
short-wavelength emission increases further. Our stellar model
does not account for these effects; thus, we likely underestimate
the strength of the radiation pressure. In the case of AU Mic,
whose UV, EUV, and X-ray emission is better constrained by
observations than that of our target, Augereau & Beust (2006)
found that this excess radiation is most important in the flare
state, when the \( \beta_{\text{rad}} \) value could even be a few times higher.

The stellar wind mass loss of magnetically active late-type
stars, as CP–72 2713 (Section 3.2), is thought to significantly
exceed the solar value (e.g., Wargelin & Drake 2001; Wood
et al. 2002). In such systems, wind forces can dominate the dust
removal (Plavchan et al. 2005; Augereau & Beust 2006;
Strubbe & Chiang 2006). Considering this corpuscular
component as well, the ratio of the radiation and wind forces
to gravitational force can be calculated following Strubbe &
Chiang (2006),

\[ \beta_{\text{rad}} = \frac{F_{\text{rad}} + F_{\text{sw}}}{F_{\text{grav}}} = \frac{3L_* \rho_{\text{sw}}}{16\pi G M_* c s}, \]

where \( \rho_{\text{sw}} = Q_{\text{pr}} + \frac{M_* \kappa_{\text{rad}} v_{\text{wind}}^2 c}{L_*} \). In this formula, \( Q_{\text{sw}} \) is the
stellar wind coupling coefficient that gives the ratio of the
effective to geometric cross section, \( M_{\text{wind}} \) is the stellar wind
mass-loss rate, and \( v_{\text{wind}} \) is the stellar wind velocity. No data
are available on the wind mass-loss rate of our target in the
literature. For the similarly active AU Mic, Augereau & Beust
(2006) derived mass-loss rates 50× and 300× higher than that
of our Sun (\( M_{\text{wind}} = 2 \times 10^{-14} M_\odot \) yr^{-1}) by taking its
quiescent phase and considering the influence of episodic flare
activity, respectively. Using these mass-loss rates and adopting
\( Q_{\text{sw}} = 1 \) and a wind velocity of 400 km s^{-1} (that corresponds
to the average wind velocity of the Sun), we recomputed the \( \beta \)
values for astro silicate particles. As Figure 3 shows, particles
with sizes smaller than ~0.013 μm in the \( M_{\text{wind}} = 50 M_\odot \) wind
scenario and ~0.09 μm in the \( M_{\text{wind}} = 300 M_\odot \) wind scenario
have a \( \beta \) value >0.5. Thus, by considering the possible wind
pressure, these small grains are blown out from the system.

The Poynting–Robertson (P-R) and stellar wind drag also
affect the dynamics of dust particles; producing effective forces
opposite to the direction of the orbital motion, these drags
result in a gradual loss of the grains’ angular momentum and
lead them to spiral into the star. Assuming a particle originally
having a circular orbit, the time necessary to reach the central
star from a radius \( R \) under the effect of P-R drag can be
computed as \( t_{\text{P-R}}(yr) = \frac{400 \times 10^3}{M_{\text{wind}} M_\odot} \frac{1}{3} \frac{R(au)}{L_\odot} \)
(Wyatt 2005). Taking the disk radius of 140 au (Section 2.3),
during the lifetime of the system (~24 Myr), only grains with \( \beta_{\text{rad}} > 0.45 \) could have spiraled into the star.
Since the collision cascade probably started well after the birth of the system (see Section 4.6), the available time is even shorter, and the threshold value for \( \beta \) is even larger. The stellar wind drag can work on a shorter
timescale. According to Plavchan et al. (2005),

\[ t_{\text{sw}} = \frac{Q_{\text{sw}}}{Q_{\text{rad}}} \]

thus, by assuming \( Q_{\text{sw}} = 1 \) and using the
adopted \( M_{\text{wind}} \) values of 50 or 300 \( M_\odot \), the timescale
of the wind drag could be ~80 or ~480 times shorter than the
P-R timescale and can result in significant inward transport of
larger dust particles as well. In the following, we will
investigate how these effects, considering the influence of
collisions, can affect the spatial distribution of grains.
4.3. Collisional Evolution

We utilized the Analysis of Collisional Evolution (ACE; Krivov et al. 2006; Löhne et al. 2008) modeling code that can simulate the collisional evolution of the disk, as well as the impact of transport processes on the dust distribution. By numerically solving the Boltzmann–Smoluchowski kinetic equation, this code enables one to follow the evolution of a disk composed of subplanetary-sized bodies down to micron-sized dust particles, considering the outcomes of collisions between these solids and the influence of the stellar gravity force and stellar radiative/corpuscular forces on them. The ACE code has already been applied successfully to explore the long-term evolution of several debris disks (e.g., Reidemeister et al. 2011; Löhne et al. 2012; Schüppler et al. 2015; Geiler et al. 2019).

In our simulations, we used the stellar and disk parameters derived in this work. We adopted a stellar mass of 0.71 $M_\odot$ and a luminosity of 0.18 $L_\odot$, while for the stellar SED, we used the ATLAS9 atmosphere model compiled in Section 3. Based on the best-fit model of the millimeter emission (Section 2.3), the parent planetesimal belt was assumed to be located between 126 and 154 au, corresponding to a radial extent of 0.2 $R_\star$, with $R = 140$ au. We set a uniform surface density for this ring. For the initial mass distribution of the solids, we assumed a power law with an index $\alpha = 1.88$ (Gáspár et al. 2012; Krivov et al. 2018). The largest planetesimals were $10^{-2}$ g ($\sim 40$ km in radius; note that this size is not constrained but was chosen to be sufficiently high to give a threshold for the collisional cascade), while the smallest particles were $10^{-11}$ g (submicron-sized). The average initial orbital eccentricity of the planetesimals was set to 0.03. Regarding the setup of the critical specific energy for disruption, we followed that described by Löhne et al. (2012). To explore the influence of the stellar wind, we performed simulations with three different wind mass-loss rates of $M_{\ast,\text{wind}} = 0$, $50 M_\odot$ yr$^{-1}$, and $300 M_\odot$ yr$^{-1}$. The wind velocity was set to 400 km s$^{-1}$ in all three models. We followed the disk evolution for 24 Myr. By assuming pure astronomical silicate (Draine 2003) as dust material, we calculated the SED of the simulated disks (for details, see Pawellek et al. 2019). We found that disk models with a mass of 50 $M_\oplus$—which include all solids up to the maximum size of 40 km—reproduce the measured SED at wavelengths $\leq 1.3$ mm well, although they cannot account for the unusually shallow millimeter SED and thus substantially underestimate the observed flux at 9 mm (see Figure 2 for an example). It is yet unclear what may be the reason for the measured low millimeter spectral index, but several different factors, including external contamination (e.g., by galaxies; see Section 3.4), may play a role. To clarify these and refine the model further, higher spatial resolution images are needed.

Using the 50 $M_\oplus$ models, we generated thermal maps at 100 and 1.3 mm. Figure 4 displays normalized surface brightness profiles as a function of radial distance at these two wavelengths after 1, 10, and 24 Myr of evolution of the disk. These profiles were compiled as the azimuthal average of the thermal maps. Assuming that the stellar wind is negligible (Figure 4a), we do not see significant differences between disks with different evolutionary states. This is consistent with the results of the above analytical calculations (Section 4.2): the stellar radiation force itself is too weak to substantially modify the grains’ orbit. However, in models with stellar wind, the inward migration of dust particles becomes efficient due to the wind drag (Figures 4b and c). At 1.3 mm, this has no significant impact on the surface brightness distribution. The thermal emission peaks at the planetesimal belt, and the inner regions are 2 orders of magnitude fainter even in the $M_{\ast,\text{wind}} = 300 M_\odot$ yr$^{-1}$ model. This finding is consistent with the results obtained by Pawellek et al. (2019) for debris disks around late-type stars with stellar wind. At 100 μm, where smaller grains dominate the emission, the influence of the wind drag is more visible; though the birth ring is still the brightest part of the disk, especially in the model with the strongest wind, the surface brightness inside the ring is only a few times lower.

4.4. Possible Signature of Stellar Wind Drag?

Interestingly, by analyzing the PACS image, we obtained a smaller disk radius (99 ± 30 au) than from the ALMA data (140 ± 14 au). Although the two estimated radii are consistent within the uncertainties, in light of the ACE results, it is worth examining whether it could be the effect of wind drag. We constructed simulated PACS images from the 100 μm thermal model maps by convolving them with our PSF model (Section 2.2). Then, using these simulated data, we derived the disk peak radius by fitting the same Gaussian ring model as we
applied in the case of the real data (Section 2.2). For most simulations, the derived peak radii were around 140 au; i.e., the surface brightness distribution is dominated by the parent belt. However, for the most extreme model with \( M_{\text{wind}} = 300 M_\odot \) at 24 Myr, we obtained a peak radius of 114 au.

This result indicates that if the stellar wind is strong enough, it may be able to shape the spatial distribution of grains so that the belt appears smaller at 100 \( \mu \)m. We note, however, that taking into account that the formation of planetesimals and then the proper stirring of the disk (see Section 4.6) needs time, the evolutionary time is likely substantially shorter than 24 Myr. Thus, if the differences between the 100 \( \mu \)m and 1.3 mm measurements are real and related to transport processes, this simulation suggests a \( M_{\text{wind}} > 300 M_\odot \) for this system.

Thanks to its large angular size and advantageous orientation, the disk around CP–72 2713 could be an ideal target to investigate the influence of wind-dominated transport in the future; however, it needs high-resolution multiwavelength observations that allow the study of the radial profile of the emitting regions.

### 4.5. Location of the Planetesimal Belt

Up to now, about two dozen debris disks have been spatially resolved at (sub)millimeter wavelengths, allowing one to constrain the location of the outer planetesimal belts in these systems. Using these data, Matrà et al. (2018) found a relationship between stellar luminosity \( L_\star \) and disk radius in the form of \( R(\text{au}) = 73 \times L_\star^{0.19} \pm 0.05 \). This formula predicts a disk radius of 53 \pm 6 au for CP–72 2713, which is significantly smaller than the measured size of 140 au. To further explore this aspect, in Figure 5, we display the outer radii\(^\text{12}\) of six debris disks (\& Eri, AU Mic, HD 61005, TWA 7, HD 92945, and HD 107146) hosted by stars with masses between 0.5 and 1.0 \( M_\odot \) (similar to that of CP–72 2713) as a function of age. We have selected only objects that are younger than 1 Gyr and whose estimated radii are based on spatially resolved millimeter observations (Booth et al. 2017; MacGregor et al. 2018; Marino et al. 2018, 2019; Daley et al. 2019; Matrà et al. 2019) and thus thought to represent the outer edge of their planetesimal belts. The age estimates of these systems are taken from the literature (Williams et al. 2004; Mamajek & Hillenbrand 2008; Bell et al. 2015; Marino et al. 2019; Zuckerman 2019). Similarly to CP–72 2713, these objects represent the most dust-rich known debris disks hosted by late-type stars in our neighborhood. As Figure 5 demonstrates, the disk radius of our target is comparable to those of HD 92945 and HD 107146 and substantially larger than those of the other three debris systems. This is especially remarkable when considering that in the case of CP–72 2713, we displayed the estimated peak radius of the belt instead of the outer radius (because of the limited angular resolution, the disk width was fixed in our modeling). Thus, CP–72 2713 is not just very dust-rich; it is also unusually extended.

Assuming that the planetesimal belt in the CP–72 2713 system is still close to its birthplace, we can expect that the predecessor protoplanetary disk must have contained a concentration of a large amount of material at the same radius. Thus, it is interesting to compare the size of our disk with the measured outer radii of protoplanetary disks around similar-mass (0.5–1.0 \( M_\odot \)) young stars. Thanks to recent ALMA observations, there is a growing sample of protoplanetary disks resolved at millimeter wavelengths in the continuum. In Figure 5, we plot the outer radii of 33 such protoplanetary disks belonging to the Taurus, Lupus, and Chamaeleon I star-forming regions marked by green, purple, and brown diamonds, respectively. The positions of the points do not represent ages but serve to better distinguish the stars belonging to different regions. The shaded region represents the 25%–75% quantiles of the disk size distribution. The whiskers correspond to the 0%–25% and 75%–100% quantiles.

### 4.6. Stirring of the Planetesimal Belt

After the dispersal of the gas-rich protoplanetary disks, the leftover planetesimals are thought to have nearly circular orbits, likely resulting in nondestructive, low-velocity collisions between them. To ignite an effective collisional cascade that produces a continuous replenishment of dust particles observable at IR and millimeter wavelengths, the planetesimal disk needs to be dynamically excited. The possible reasons for this dynamical excitation are still debated in the literature. The most commonly invoked explanations require the existence of a giant planet or a stellar companion somewhere in the system (planetary or binary stirring; Mustill & Wyatt 2009) and/or the presence of large planetesimals embedded in the belt.

\(^{12}\) In the case of HD 61005, MacGregor et al. (2018) modeled the observed millimeter data using a two-component model composed of a planetesimal belt and an outwardly extended halo. In our study, we used the outer radius of the planetesimal belt component (67 au).
(self-stirring; Kenyon & Bromley 2008). In our solar system, both self-stirring and planetary stirring may contribute to the excitation of the Kuiper Belt, resulting in a high excitation level there (Matthews et al. 2014). However, our knowledge is limited on the origin of stirring in other debris disks (Moór et al. 2015; Krivov & Booth 2018). All proposed stirring mechanisms need time to be activated in a given part of the disk. Using the model predictions, we can thus examine their feasibility in the CP−72 2713 system.

According to the classical version of the self-stirring model (Kenyon & Bromley 2008), mutual low-velocity collisions between smaller bodies in a dynamically cold region of the disk lead to the formation of gradually larger planetesimals. Kenyon & Bromley (2008) found in their simulations that after reaching a radius of ∼1000 km, the largest planetesimals can stir their environment efficiently. It makes collisions between their smaller neighbors destructive and leads to the production of debris material through a collisional cascade. Adopting an initial protoplanetary disk with a surface density distribution of \( \Sigma(a) = 0.18(M_\text{d}/M_\odot)x_m(r/30 \text{ au})^{-3/2} \text{ g cm}^{-2} \), where \( x_m \) is a scaling factor (for the minimum-mass solar nebula \( x_m = 1 \)), Kenyon & Bromley (2008) provided an analytical formula for the formation time of 1000 km−sized planetesimals (the onset time of the stirring) at a stellocentric radius \( r \):

\[
t_{\text{onset}}^\text{classical} = 145x_m^{-1.15}\left(\frac{r}{80 \text{ au}}\right)^3\left(\frac{2M_\odot}{M_*}\right)^{3/2} \text{ Myr}. \tag{4}
\]

Realistically, the \( x_m \) factor could not be higher than 10 (Mustill & Wyatt 2009). Taking a disk with the above-described radial surface density profile with \( x_m = 10 \), and assuming that the location of the planetesimal belt at 140 au in the CP−72 2713 system corresponds to the outer edge of the initial protoplanetary disk, the total initial mass of solids would have been ∼1.2 × 10^3 M_\odot. This hugely exceeds the measured dust masses of protoplanetary disks around similar-mass stars in the Lupus and Chameleon I star-forming regions (Ansdell et al. 2016; Pascucci et al. 2016), further confirming the usage of \( x_m = 10 \) as a strong upper limit.\(^{13}\)

In Figure 6, we plot the onset time of the stirring at different radii for \( x_m = 1 \) and 10 (solid cyan lines). A comparison with the location of the planetesimal belt in the CP−72 2713 system (red circle) demonstrates that even with \( x_m = 10 \), the radius of the predicted stirring front is very far from the region of the observed planetesimal belt at the age of the system.

The collisional coagulation model is not the sole feasible way for large planetesimals to form. Particle concentration models predict a significantly quicker formation of larger bodies even far from the star (at \( r > 100 \text{ au} \)) through gravitational collapse of locally concentrated pebbles (Johansen et al. 2015; Krivov & Booth 2018, and references therein). According to these scenarios, large planetesimals are already present in the disk by the time of the dissipation of the gas-rich protoplanetary material. Due to the possibly smaller size of the largest bodies (a few hundred km; Simon et al. 2016; Schäfer et al. 2017) with respect to the classical model (where the 1000 km−sized planetesimals can stir the neighboring disk promptly), the excitation of the surrounding smaller bodies takes more time than in the previous scenario. According to

\(^{13}\) We note that Kenyon & Bromley (2008) derived Equation (4) by fitting their model results for disks with \( x_m \) values between 1/3 and 3.

![Figure 6. Onset time of the stirring as a function of stellocentric radius for different stirring scenarios (Section 4.6). The red circle corresponds to the observed property of the CP−72 2713 system.](image)

Krivov & Booth (2018), in this scenario, the onset time of effective self-stirring at a radius \( r \) can be computed as

\[
t_{\text{onset}}^\text{pebble} = \left(\frac{129}{\gamma x_m}\right)^{1/3} \left(\frac{\rho}{1 \text{ g cm}^{-3}}\right)^{1/3} \left(\frac{V_{\text{frag}}}{30 \text{ ms}^{-1}}\right)^4 \left(\frac{S_{\text{max}}}{200 \text{ km}}\right)^{-3/2} \left(\frac{M_*}{M_\odot}\right)^{3/2} \left(\frac{r}{100 \text{ au}}\right)^3 \text{ (Myr)}, \tag{5}
\]

where \( \gamma \) is a parameter in Equation (20) in Krivov & Booth (2018), \( \rho \) is the bulk density of planetesimals, \( V_{\text{frag}} \) is the minimum collisional velocity needed for fragmentation, and \( S_{\text{max}} \) is the size of the largest planetesimals. Figure 6 shows—by using the default values proposed by Krivov & Booth (2018) of \( \gamma = 1.5, \rho = 1 \text{ g cm}^{-3}, V_{\text{frag}} = 30 \text{ ms}^{-1} \), and \( S_{\text{max}} = 200 \text{ km} \)—that the outer edge of the possibly stirred region (purple dashed-dotted line) is close to the position of the planetesimal belt in the CP−72 2713 system. Here we again adopted \( x_m = 10 \). Considering the caveats of the model and the uncertainties of the fundamental model parameters (Krivov & Booth 2018), this means that the excitation of the CP−72 2713 disk can be consistent with the pebble concentration stirring model. For instance, by adopting somewhat larger maximum planetesimal sizes of \( S_{\text{max}} = 230 \text{ km} \), the model would predict exactly 24 Myr for the onset of stirring at 140 au, the location of the belt.

Dynamical excitation of a planetesimal disk can also be caused by a planet via its secular perturbation (Wyatt 2005; Mustill & Wyatt 2009). Similar to the self-stirring scenario, the gravitational influence of a planet located within the planetesimal belt manifests in an outward propagating stirring front. Using the model developed by Mustill & Wyatt (2009) and assuming a Saturn-mass planet with an orbital radius of 65 au (roughly corresponding to the orbital radius of the outermost planet in the HR 8799 system) and a moderate eccentricity of 0.1, we found that the perturbation induced by such a planet could just reach the region of the belt by the age of the system.
(Figure 6). The same result can be obtained with a smaller planetary mass if the semimajor axis and/or the eccentricity of the orbit is larger. Thus, planetary stirring is a feasible model for the CP−72 2713 system.

Finally, we cannot exclude the possibility that the planetesimal belt is prestirred, i.e., born stirred (Wyatt 2008) because of some not-yet-specified physical mechanism. In this scenario, \( t_{\text{onset}} = 0 \) at all radii.

5. Summary

In this paper, we present the results of our multiwavelength observations of a cold debris disk that we identified around CP−72 2713, a K7/M0-type member of the \(~\)24 Myr old BPMG. By analyzing the obtained SED, we found that the excess spectrum is almost identical to a pure blackbody with a temperature of 43 K and a fractional luminosity of \( 1.1 \times 10^{-3} \). No CO line emission was detected in the disk. The derived dust fractional luminosity is prominently high; we know of only four other similarly dust-rich Kuiper Belt analogs within 40 pc of the Sun.

Herschel and ALMA images revealed that the observed emission at 100 \( \mu m \) and 1.3 mm is spatially resolved. Analysis of these data allowed us to explore the basic disk morphology. Based on the derived disk orientation, there is no evidence for any significant misalignment between the stellar equator and the disk plane; both are inferred to be inclined by \(~45^\circ\). Adopting a symmetric Gaussian radial surface brightness profile, our modeling yields disk radii of \( 99^{+22}_{-26} \) and \( 140 \pm 14 \) au using the 100 \( \mu m \) and 1.3 mm data, respectively. By analyzing the possible dust removal mechanisms and the collisional evolution of the disk using the ACE code, we found that those large grains that dominate the observed millimeter emission are likely not moved significantly away from their birth location and thus well trace the parent planetesimal belt. Smaller grains emitting at 100 \( \mu m \), however, might spread inward if the stellar wind is strong enough, potentially explaining the smaller radius found with Herschel.

A planetesimal belt radius of \(~140 \) au is one of the largest among known debris disks hosted by low-mass stars. In our neighborhood, we know of only a few protoplanetary disks around \(~0.5−1.0 M_\odot \) stars that contain a substantial amount of dust material at 140 au, i.e., the location of the planetesimal belt in CP−72 2713. Supposing that this planetesimal belt was already at the same place when it was formed, it could be the offspring of a very extended protoplanetary disk.

We also examined the possible dynamical excitation of the planetesimal belt. By applying different stirring models, we found that the presence of dust-producing planetesimals at a radius of \(~140 \) au is incompatible with the classical self-stirring scenario that assumes slow incremental growth of planetesimals. Stirring by a planet or self-stirring by planetesimals formed rapidly by pebble concentration, however, can explain the dust production even in this extended young disk.

Both AU Mic and CP−72 2713 belong to the BPMG, suggesting that they were born in the same star-forming cloud at approximately the same time. The two systems show further resemblances: their late-type active central stars are surrounded by cold debris disks. Therefore, considering its somewhat more massive host star and more dust-rich and extended debris disk, CP−72 2713 appears to be a massive analog (a big sibling) of AU Mic. Being the first representative of debris disks orbiting a low-mass star, AU Mic has been the target of many different studies (e.g., Augereau & Beust 2006; MacGregor et al. 2013; Boccaletti et al. 2015) and played a central role in understanding the physical mechanisms that can shape circumstellar material in such systems (Strubbe & Chiang 2006; Schüpfner et al. 2015).

The disk of CP−72 2713 has a similar angular size to that of AU Mic, but it is closer to face-on, which makes it a more favorable target to investigate the spatial structure of debris disks around low-luminosity stars.

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Software: CASA (McMullin et al. 2007), umultitfit (Martí-Vidal et al. 2014), mpfit (Markwardt 2009), MOPEX (Makovoz & Marleau 2005), FLT/W/RM code (Vida & Roettenbacher 2018), MUFRA1 (Kollath 1990), Stilism (Capitanio et al. 2017; Lallement et al. 2018).

Appendix

Analysis of the TESS Data

The star CP−72 2713 was observed in 2 minute (short) cadence by camera 3 of the TESS spacecraft in sectors 1 (between 2018 July 25 and August 22) and 13 (between 2019 June 19 and July 18). In our analysis, we utilized the simple aperture photometry (SAP) light curves that were downloaded from the MAST archive.\(^{14}\) We removed data points where the quality flags indicated problems using the bitwise AND operation with the binary mask 101010111111, as suggested by the TESS Data Product Overview.\(^{15}\) The zero-point of the TESS magnitude scale (i.e., the magnitude–flux conversion factor) has been set using the Gaia DR2 RP magnitude (Gaia Collaboration et al. 2018) by exploiting the almost complete overlap of the corresponding response functions at the far optical red and near-IR regimes (see Figure 1 in Ricker et al. 2015 and Figure 3 in Jordi et al. 2010). The obtained light curves show a clear periodic modulation likely due to rotation of stellar spots (Figure A1).

For the Fourier analysis of the short-cadence light curves, we subtracted a linear fit from the observations from each sector. Although these could be caused by either real intrinsic changes or instrumental artifacts, due to the distribution of the data points, it is not possible to reliably fit variations on this timescale with Fourier components. The remaining data were analyzed

\(^{14}\) https://mast.stsci.edu

\(^{15}\) https://outerspace.stsci.edu/display/TESS/2.0+Data+Product+Overview
using MUFRAN (Kolláth 1990). The main feature in the Fourier spectrum of the light curve (see Figure A2) is connected to the rotation \( P = 4.437 \) days; the other peaks—an order of magnitude weaker—are either present at the double frequency of this signal or close to the main rotation period. These latter peaks could be a result of spots located at different latitudes showing a slightly different rotation rate due to differential rotation. A weak trend with the length of approximately the observing runs is also present.

Flares in the light curve were identified using the FLATWRM code (Vida & Roettenbacher 2018), which uses a machine-learning algorithm to give a robust model of the light curves in order to detect flare events and a voting system implemented to keep false-positive detections to a minimum. We originally set a 3\( \sigma \) detection limit that was lowered to 2\( \sigma \) as visual inspection of the results proved that there were no false positives identified. The minimum number of data points for a flare was set to 3, and the degree of polynomials to describe light curves was set to 10. In the light curve, 51 events were identified; altogether, 1.24\% of the data was considered part of a flare event. All of the eruptions are relatively weak, and each has an amplitude of \(< 0.04\text{ mag.}\)

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![Figure A1. TESS short-cadence light curves of CP−72 2713 measured in (left) sector 1 and (right) sector 13.](image)

![Figure A2. Fourier analysis of the TESS light curve. The upper five panels show the Fourier spectra of the light curve after prewhitening with the dominant frequency, marked with a dash (note: the top plot has a different y-scale). The lower two panels show the spectral window and residual light curve (note: the largest flare is cropped).](image)
