Herschel OBSERVATIONS OF DUST AROUND THE HIGH-MASS X-RAY BINARY GX 301–2

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ABSTRACT

We aim at characterizing the structure of the gas and dust around the high-mass X-ray binary GX 301–2, a highly obscured X-ray binary hosting a hypergiant (HG) star and a neutron star, in order to better constrain its evolution. We used Herschel PACS to observe GX 301–2 in the far infrared and completed the spectral energy distribution of the source using published data or catalogs from the optical to the radio range (0.4 to $4 \times 10^4 \mu\text{m}$). GX 301–2 is detected for the first time at 70 and 100 $\mu\text{m}$. We fitted different models of circumstellar (CS) environments to the data. All tested models are statistically acceptable, and consistent with an HG star at $\sim 3$ kpc. We found that the addition of a free–free emission component from the strong stellar wind is required and could dominate the far-infrared flux. Through comparisons with similar systems and discussion on the estimated model parameters, we favor a disk-like CS environment of $\sim 8$ AU that would enshroud the binary system. The temperature goes down to $\sim 200$ K at the edge of the disk, allowing for dust formation. This disk is probably a rimmed viscous disk with an inner rim at the temperature of the dust sublimation temperature ($\sim 1500$ K). The similarities between the HG GX 301–2, B[e] supergiants, and the highly obscured X-ray binaries (particularly IGR J16318–4848) are strengthened. GX 301–2 might represent a transition stage in the evolution of massive stars in binary systems, connecting supergiant B[e] systems to luminous blue variables.

Key words: circumstellar matter – stars: early-type – stars: evolution – stars: individual (BP Cru, Wray 977) – X-rays: binaries – X-rays: individual (GX 301-2)

Online-only material: color figures

1. INTRODUCTION

Massive stars (more than about eight times the mass of the Sun, e.g., Heger et al. 2003) have been key players in the cosmic history through their enormous input of ionizing photons, energy, momentum, and chemical species into the universe. In addition, the hot, massive stars can episodically form enormous quantities of dust. The presence of dust and its distribution provide primary information on the evolution of those massive stars (e.g., Kochanek 2011).

While cool star winds readily form dust (see the review by Willson 2000), the intense radiation fields of young, massive stars would be expected to prevent dust formation in their circumstellar (CS) environment. However, dust is observed around some young massive stars, for example in a subset of Carbon Wolf–Rayet (WR) stars containing binaries with colliding winds (e.g., Crowther 2007), in luminous blue variables (LBVs) that show large dusty shells (see the review by Humphreys & Davidson 1994), or in supergiants showing the B[e] phenomenon (Zickgraf et al. 1986; Zickgraf 1998). SgB[e] stars are early-type stars with the simultaneous presence of low-excitation forbidden line emission and strong infrared excess in their spectra (Zickgraf 1998; Lamers et al. 1998). They share some observational properties with LBVs that are identified as luminous, hot, unstable supergiants that suffer irregular eruptions like S Dor and AG Car, or more rarely, giant eruptions like P Cyg and η Car (Humphreys & Davidson 1994). All those rare types of stars have in common a rapid mass loss in a dense wind and may represent some of the latest stages of the evolution of massive stars that lead to supernovae (SNe, e.g., Langer 2012).

It is not always clear whether those different classifications represent stars with different initial conditions or stars at different evolutionary stages. It is, however, clear that dust can be formed around massive stars under specific conditions: strong stellar winds (responsible for high CS densities and thus shielding the dust grains from the stellar ionizing radiation), a high abundance of heavy elements (increasing the probability of dust formation), and clumping of the CS material (locally increasing the density). Those conditions are natural around massive ($>20 M_\odot$) and luminous ($>10^5 L_\odot$) objects, such as WR stars, hot supergiants, and LBVs.

Another key parameter that could be related to the presence of CS dust around those massive stars may be binarity. Indeed, according to Sana et al. (2012), binary interaction dominates the evolution of massive stars: over 70% of all massive stars exchange mass with a companion, leading to a binary merger in one third of the cases. For sgB[e], it is suggested that the dust can be present in the outer parts of an equatorial disk that probably forms through the bi-stability mechanism (Lamers & Pauldrach 1991) and possibly fast rotation (Bjorkman & Cassinelli 1993). Podsiadlowski et al. (2006) noticed that binary mergers produce an initially rapidly rotating merged object that is an excellent candidate for sgB[e] progenitors. Furthermore, Miroshnichenko (2007) proposed that sgB[e] and their low-luminosity counterparts (FS CMa objects) are currently undergoing or have recently undergone a phase of rapid mass exchange in a binary system, associated with a strong
mass loss and dust formation. Mass transfer in close binary systems with massive stars could then have an important role in shaping the structure of the diffuse CS environment (e.g., Plets et al. 1995; Millour et al. 2011).

In many cases, the inferred companion star could be much fainter than the massive primary and may have remained undetected. Among binary stars with a massive primary, high-mass X-ray binaries (HMXBs) are interesting test cases as the (pulsed) X-ray emission provides detailed information on the binary composition, orbital parameters, and environment. Those may represent a new stage in the complex evolution of massive stars. In particular, a growing number of highly obscured HMXBs has been revealed by the INTEGRAL hard X-ray observatory (Matt & Guainazzi 2003; Filliatre & Chaty 2004; Walter et al. 2006; Chaty & Rahoui 2012; Coleiro & Chaty 2013, see also Chaty 2013 for a recent review). Those systems may harbor super or hypergiant (HG) stars in binaries with a compact object and enshrouded in a dense CS environment, probably hosting dust. We performed Herschel observations in the mid-infrared of six supergiant HMXBs in order to test the presence of dust and better understand its structure in those objects (see preliminary results in Chaty et al. 2013), and focus here on GX 301–2.

GX 301–2 is an obscured HMXB system consisting of an accreting neutron star fed by the stellar wind of a blue HG B1 Ia+ star (cataloged as Wray 977, or BP Cru, see, e.g., Lewin et al. 1971; Jones et al. 1974; Kaper et al. 1995, 2006). The absorption varies from $10^{22}$ to $10^{24}$ atoms cm$^{-2}$ (Mukherjee & Paul 2004) and the reddening is around $E(B−V) = 1.96$ (Kaper et al. 2006). The system has an orbital period of $\sim 41.5$ days with an eccentricity of 0.46 (Koh et al. 1997), and GX 301–2 is one of the slowest known pulsars, with a period that slowly varies between 675 and 700 s (White et al. 1976; Pravdo et al. 1995; Evangelista et al. 2010). The magnetic field is around $4 \times 10^{12}$ G, indicating a classical pulsar (Kreykenbohm et al. 2004). The X-ray mass function of the system has been estimated to be $\sim 31.9 M_{\odot}$ (Sato et al. 1986), the highest known for a HMXB with a pulsar companion, giving a mass of $43 \pm 10 M_{\odot}$ for the companion star and $1.85 \pm 0.6 M_{\odot}$ for the neutron star (Kaper et al. 2006). The X-ray light curve is characterized by bright flares occurring just before periastron passage of the neutron star (Watson et al. 1982). Those are clearly visible in the X-ray light curve from the Swift Burst Alert Telescope (see Figure 1). The distance of GX 301–2 has been estimated to be $3.1 \pm 0.6$ kpc using a spectral energy distribution (SED) fitting procedure (Coleiro & Chaty 2013), consistent with the 3–4 kpc range proposed earlier (Kaper et al. 2006). Therefore the line of sight crosses the Southern Coalsack (e.g., Kaper et al. 2006) and passes through one or more spiral arms in our Galaxy, potentially contaminating the emission.

Kaplan et al. (2006) and Moon et al. (2007) studied the CS environment of the system and reported the presence of dust around the system through the detection of silicate absorption features and continuum components with low temperatures. However, they do not explore the geometry of this CS component. Moon et al. (2007) noticed the presence of low ionization potential forbidden emission lines and discuss similarities with LBVs in the mid-infrared spectra.

In this paper, we report on new Herschel observations of GX 301–2 (Section 2) and model the emission of the source in the wavelength domain from 0.4 to $4 \times 10^4$ $\mu$m in order to characterize the geometry of the CS environment. We detail the models used in Section 3, give the results of the fits to the data in Section 4, and discuss the properties and the possible geometries of the CS environment of GX 301–2 in Section 5.

2. DATA ACQUISITION AND PROCESSING

We performed sensitive far-infrared (60–210 $\mu$m) observations of GX 301–2 on 2011 August 2 with the ESA Herschel Space Observatory (Pilbratt et al. 2010), in particular employing Herschel’s large telescope and powerful science payload to do photometry using the PACS instrument (Poglitsch et al. 2010). At the date of the observations, the binary system was at its periastron, right after the periodic X-ray flare that can be seen in Figure 1. Observations were performed in the three available bands (blue 60–85 $\mu$m, green 85–130 $\mu$m, and red 130–210 $\mu$m) in mini-scan map mode: medium speed, 10 scan legs of 25 length with 2.0 cross-scan step, with orientation angles at 70° and 110°; and repetition factors of 5 and 10 for each orientation angle for the blue/red and green/red filters, respectively. This leads to a total integration time of 800, 1600, and 2400 s in the blue, green, and red band, respectively.

The images are shown in Figure 2 where a point source corresponding to GX 301–2 can be seen in the center of the frame. The point source appears to be surrounded by an extended structure. Based on IRAS observations, Hutchcroft & Kaper (2002)

![Figure 1](image1.png)

**Figure 1.** X-ray light curve of GX 301–2 with Swift/BAT (15–150 keV). The vertical lines indicate the periastron passages (based on Koh et al. 1997) and the red dashed vertical line shows the epoch of the Herschel/PACS observations on MJD 55775.05 right after periastron. (A color version of this figure is available in the online journal.)

![Figure 2](image2.png)

**Figure 2.** Herschel/PACS images centered on GX 301–2 (indicated by an arrow). From left to right, the blue, green, and red bands are shown (70, 100, and 160 $\mu$m). The size of the snapshots is 2.5 $\times$ 2.5. North is up, east is left. (A color version of this figure is available in the online journal.)
suggested that the extended structure could be a wind bow shock (see their Figure 4). We further analyze the extended emission and possible cavity around GX 301–2 in a companion paper (A. Coleiro et al., in preparation).

We used HIPE (Ott 2010) to reprocess the data with custom scripts for PACS (M. Sauvage 2013, private communication). The software getsources (Men’shchikov et al. 2012) was then used to detect the sources and filaments, and to extract fluxes using a multi-wavelength and multi-scale method. As the source is faint and the structure of the background complex, we masked the area outside a 2.4 × 1.7 region around the target to avoid the presence of extended features seen at the edges of the images in Figure 2. We detected a point source at the position of GX 301–2 in the blue and green bands with fluxes of 61.0 ± 0.6 and 61.2 ± 14.9 mJy (with significances of 15.4σ and 3.8σ, respectively). No significant detection was made for the red band with a detection limit of 250 mJy at 3σ (note the presence of a nearby extended source blended with the point source).

The optical–infrared SED was completed using B- and V-band magnitudes from the Tycho-2 catalog (Høg et al. 2000), and JHKs magnitudes from the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006). We included fluxes at 3.6, 4.5, 5.8, and 8.0 μm from the Galactic Legacy Infrared Midplane Survey Extraordinary catalog based on observations with IRAC on board Spitzer (Benjamin et al. 2003; Churchwell et al. 2009). As the central pixels of the source were saturated at 3.6 and 4.5 μm, we used the flux values estimated by Kaplan et al. (2006). We finally included fluxes at 12 and 22 μm obtained with the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) and fluxes at 8.28, 12.13, and 14.65 μm obtained with the Midcourse Space Experiment (MSX; Price et al. 2001). The flux measurements from various observatories are reported in Table 1. Within the errors, the infrared measurements with different instruments are consistent. We thus used all these data simultaneously to characterize the emission of the source.

GX 301–2 was also observed at radio wavelengths (Pestalozzi et al. 2009) with ATCA (4.8 and 8.6 GHz) at 12 epochs spread between 2008 November and 2009 February. Pestalozzi et al. (2009) found that the radio source showed a negative index during the X-ray outburst, and a positive index otherwise, though with large error bars. They suggest that the radio emission originates in two components: a persistent thermal emission from the wind of the HG mass donor Wray 977 and an episodic emission, perhaps a weak jet, that appears at the time of the X-ray outburst. The mean flux at 8.6 GHz when the source is detected is 0.72 ± 0.16 mJy. To estimate the flux due to the presence of strong winds around massive stars, we used Equation (4) in Scuderi et al. (1998) and input parameters estimated by Kaper et al. (2006; i.e., a mass loss rate of $\dot{M} = 10^{-5} M_\odot$ yr$^{-1}$, a temperature of $T = 18,100$ K, and a terminal velocity of the wind of $v_{\inf} = 305$ km s$^{-1}$). We thus expect a 8.6 GHz flux of 2.5 mJy for GX 301–2. The discrepancy possibly indicates a lower mass loss rate or larger distance, but the radio flux from a stellar wind can naturally vary by a factor of a few (Scuderi et al. 1998). During our Herschel observations, we can nevertheless expect free–free emission from the stellar wind, which may have some contribution to the mid-infrared emission down to ~10 μm with a positive spectral index $\alpha = 0.6$ ($S_{\nu} \propto \nu^\alpha$; Wright & Barlow 1975).

### Table 1

| Band Name | Wavelength ($\mu$m) | Band Width ($\mu$m) | Flux (Jy) | Flux Error (Jy) | Note |
|-----------|-------------------|--------------------|-----------|----------------|------|
| B         | 0.441             | 0.102              | 0.034     | 0.012          |      |
| V         | 0.551             | 0.089              | 0.206     | 0.014          |      |
| J         | 1.242             | 0.240              | 3.28      | 0.07           |      |
| H         | 1.651             | 0.267              | 3.80      | 0.10           |      |
| Ks        | 2.166             | 0.282              | 3.59      | 0.07           |      |
| WISE-1$^a$ | 3.535           | 0.663              | 0.47      | ...           | Saturated, Wright et al. (2010) |
| IRAC-1    | 3.6               | 0.77               | 2.0       | 0.2            |      |
| IRAC-2    | 4.5               | 1.06               | 1.6       | 0.2            |      |
| WISE-2$^a$ | 4.603           | 1.042              | 0.70      | ...           | Saturated, Wright et al. (2010) |
| IRAC-3    | 5.8               | 1.43               | 1.16      | 0.12           |      |
| ISO-LW2$^a$ | 6.75            | ...                | 0.837     | ...           |      |
| IRAC-4    | 8.0               | 2.9                | 0.78      | 0.08           |      |
| MSX-A     | 8.28              | 3.36               | 0.63      | 0.07           | Price et al. (2001) |
| AK09$^a$  | 9.0               | 4.9                | 0.60      | 0.02           | Ishihara et al. (2010) |
| ISO-LW10$^a$ | 11.5           | ...                | 0.517     | ...           | Kaper et al. (2006) |
| WISE-3    | 11.560            | 5.507              | 0.41      | 0.01           | Wright et al. (2010) |
| MSX-C     | 12.13             | 1.72               | 0.45      | 0.05           | Price et al. (2001) |
| MSX-D     | 14.65             | 2.23               | 0.32      | 0.03           | Price et al. (2001) |
| AK18$^a$  | 18.0              | 11.7               | 0.20      | 0.03           | Ishihara et al. (2010) |
| WISE-4    | 22.088            | 4.101              | 0.22      | 0.01           | Wright et al. (2010) |
| ISO-PHT3$^a$ | 25             | ...                | 0.089     | ...           | Kaper et al. (2006) |
| PACS-B    | 70                | 20                 | 0.061     | 0.0066         | This work |
| PACS-G    | 100               | 40                 | 0.061     | 0.0149         | This work |
| 8.6 GHz   | 34860             | 600                | 0.72 × 10$^{-3}$ | 0.16×10$^{-3}$ | Pestalozzi et al. (2009) |

**Notes.** See the references in the text.

$^a$ These points were not used in the modeling as they have lower precision (due to saturation, large bandwidth, or large errors).
We used the stellar photosphere model of Castelli & Kurucz (2004, hereafter CK04), and the stellar parameters derived by Kaper et al. (2006) for the star Wray 977 associated with GX 301–2: $T = 18,100$ K, $\log(g) = 2.38$, and $R = 70 R_\odot$ for a distance $D = 3040$ pc. We thus selected the closest available CK04 model with $T = 18,000$ K and $\log(g) = 2.5$ and kept the radius of the star fixed.

We also built an extinction law following Cardelli et al. (1989) in the visible, Indebetouw et al. (2005) between 1.25 and 8.0 $\mu$m, Lutz et al. (1996) between 8.0 and 24 $\mu$m, and Moneti et al. (2001) above 24 $\mu$m. The main parameter for the extinction law is the excess color $E(B - V)$. We adopt $R_V = A_V/E(B - V) = 3.1$ (see, e.g., Savage & Mathis 1979).

As the reddening is high for GX 301–2, the extinction law has a large impact on the shape of the SED. In particular, broad silicate absorption lines around 10 and 20 $\mu$m are visible and taken into account in the extinction law (Lutz et al. 1996). The obtained extinction law is particularly well suited for the case of GX 301–2, being largely based on observations in the Galactic center and the Galactic plane. However, there could be local fluctuations of this law that are still not properly measured.

The optical–infrared SED of GX 301–2 has already been fitted between 1 and 10 $\mu$m by Kaplan et al. (2006) using two components: the star and a spherical blackbody emission with temperature 740 K and an extension $R_{\text{dust}} = 9 \times R_{\text{star}}$ to model the surrounding dust. Using Spitzer data up to 38 $\mu$m, Moon et al. (2007) found that multiple emission components were required to model the continuum emission of the dust (a hot component with $T \sim 700$ K and a warm component with $T \sim 180$ K).

In order to constrain the geometry of the CS environment, we considered several models that could explain the infrared excess found in this source: (1) a power law spanning several orders of magnitude, (2) spherical blackbody dust components (as in Kaplan et al. 2006 and Moon et al. 2007), and (3) disk-like dust components. For (2) and (3), we also tested the addition of a power law with a fixed spectral index $\alpha = 0.6$ and the observed flux at 8.6 GHz in order to model the free–free emission from the stellar wind detected by Pestalozzi et al. (2009).

GX 301–2 appears to be similar to two obscured X-ray binary systems hosting sgB[e] stars: IGR J16318–4848 (Revnivtsev et al. 2003; Filliatre & Chaty 2004; Kaplan et al. 2006; Moon et al. 2007; Chaty & Rahoui 2012), which presents a CS disk with dust, and XTE J0421+560 (CI Cam), for which IRAS 12–100 $\mu$m data suggested the existence of a substantial CS dust shell (Belloni et al. 1999; Clark et al. 1999). We thus investigate the possibility of having a similar distribution of dust as a disk surrounding the HG star, as is generally observed for sgB[e]. Lamers et al. (1998) pointed out that the CS envelope geometry is most probably disk-like for those stars, which naturally provides conditions for a high density of the CS material and, as a consequence, for shielding of CS dust from the ionizing stellar radiation. We thus used a similar model to the one proposed by Chaty & Rahoui (2012) for IGR J16318–4848, initially based on the dust structure of Herbig Ae/Be stars (Monnier et al. 2005). The CS environment of those objects is well described as a simple disk model possessing a central optically thin (dust-free) cavity, ringed by hot dust—a rim—emitting at the expected sublimation temperature ($\sim 1500$ K), hereafter called a rimmed disk. For some systems, however, the inner gas in the mid-plane may be optically thick, partially shielding the innermost dust from stellar radiation and causing the dust sublimation radius to shrink for the same sublimation temperature. This would correspond to a classical disk model.

We assumed that the disk is completely flat with a ring-like rim of constant temperature $T_{\text{rim}}$, located at an inner radius $R_{\text{in}}$, and of width $H_{\text{rim}}$, as in Lachaume et al. (2007). The equation used to model the flux can therefore be written as

$$F_* (v) = \left( \frac{R_*}{D} \right)^2 \times \text{CK04}(v, T_*) + 2\pi \frac{H_{\text{rim}} R_{\text{in}}}{D^2} F_{\text{rim}}(v, T_{\text{rim}}) + 2\pi \frac{\cos(i)}{D^2} \int_{R_{\text{in}}}^{R_{\text{out}}} r B(v, T(r))dr,$$

where $T_*$, $R_*$, and $D$ are, respectively, the temperature, the radius, and the distance of the companion star and CK04 is the stellar photosphere model (Castelli & Kurucz 2004). $B(v, T)$ is the Planck function at the frequency $v$. The disk is defined by $i$, $T_{\text{in}}$, and $R_{\text{out}}$, which are, respectively, the inclination of the disk, the temperature at the inner radius $R_{\text{in}}$, and the outer radius. $T(r) = T_{\text{in}} (r/R_{\text{in}})^{-\alpha}$ is the disk temperature at a given radius $r$, where $q$ is a dimensionless parameter generally ranging from 0.5 to 0.75 (irradiated to viscous disk Chiang & Goldreich 1997).

We fixed the inclination to $60\degree$ as estimated by Kaper et al. (2006) for the inclination of the binary system, assuming that the inclination of a disk around the companion star would be similar. We only considered the case of a viscous disk ($q = 0.75$), as expected for this kind of system (e.g., Okazaki 2007). It is clear from Equation (1) that we expect degeneracies in the fits between the radii $R_*$, $R_{\text{in}}$ and the distance $D$, so the absolute value of those parameters should be taken with care. There is also a degeneracy between $H_{\text{rim}}$ and $R_{\text{in}}$, we thus arbitrarily fixed $H_{\text{rim}}$ to $15 R_\odot$ following the results of Chaty & Rahoui (2012).

4. FIT RESULTS

We report the results of the SED fitting in Table 2 and plot the data and models in Figures 3–6.

We first tried to fit a power law in addition to the CK04 stellar photosphere model (and including the extinction law). We found a statistically acceptable fit with an index $\alpha = 0.75 \pm 0.01$ (see Table 2). This index is different from the 0.6 expected for stellar winds (Wright & Barlow 1975). There is a deviation from the model in one Herschel energy band (accounting for most of the $\chi^2$ excess, see Figure 3) that may indicate a marked curvature in the spectrum and the necessity of exploring more complex models.

In order to account for the presence of dust around the system (see Moon et al. 2007), we fitted a spherical blackbody component (as in Kaplan et al. 2006) instead of the power law and found a low temperature of $T_\nu = 411 \pm 47$ K and radius of $R_\nu = 1288 \pm 197 R_\odot$ (see Figure 4, left). We note that the Herschel/PACS data points are well above the model, resulting in a reduced $\chi^2$ of 3.95 with 12 dof. We obtained a slightly lower temperature in our fit compared to Kaplan et al. (2006). Following Moon et al. (2007), we fixed all the parameters and added a second blackbody component to account for this mid-infrared excess. We found a low temperature of 70 K and rather large radius of $\sim 6000 R_\odot$ for this second component. If we thaw the parameters and add instead a component from the stellar wind corresponding to the observed radio flux and with a spectral index of $\alpha = 0.6$, the reduced $\chi^2$ is improved to...
2.16, with a similar temperature and slightly smaller radius (see Figure 4, right). Given the low number of degrees of freedom in our fits, the standard deviation from the expected reduced $\chi^2$ of 1 is large. Using Gaussian approximation, the width of the $\chi^2$ distribution would be 0.4, but it is likely larger in our case (see, e.g., Andrae et al. 2010). The reduced $\chi^2$ results we obtained for models presented in Figure 4 are thus barely acceptable in theory but cannot be completely ruled out. We note that there is a large spread in the residuals for the $JHKs$ bands and indication of a different curvature than the proposed model (dominated by the stellar photosphere model and the extinction law in those bands).

We then used a classical viscous disk model (as described in Section 3) in addition to the CK04 model and obtained acceptable fits (see Figure 5 and Table 2). The inner temperature of the disk is consistent with the dust sublimation temperature ($\sim 1500$ K). The addition of a power law corresponding to the stellar wind slightly improved the fit and drastically changed the extension of the disk from $R_{\text{out}} \sim 4200$ to $1800 R_\odot$. This would correspond to $\sim 25$ stellar radii, or $\sim 8$ AU. With this model, the residuals for the $JHKs$ bands are not improved. At the outer edge of this classical disk, the temperature drops to $\sim 150$ K.

Finally, we fitted the SED with the rimmed disk model defined in Equation 1 (see Section 3) and report the results in Figure 6 and Table 2. We obtained the best fits with this model and, in particular, flatter residuals for the $JHKs$ bands thanks to the rim component that dominates the contribution to the near-infrared excess. The temperature of the rim is consistent with the dust sublimation temperature as expected for this kind of model (see Section 3 and Monnier et al. 2005). The addition of a power-law component (stellar wind) again drastically changed the extension of the disk, reaching a similar value to that found for the classical disk, around $1800 R_\odot$. At the outer edge of this rimmed disk, the temperature drops to $\sim 250$ K.

5. DISCUSSION

Using all the available visible–infrared photometry on GX 301–2, with the addition of Herschel and radio data points for the first time, we fitted spherical and disk-like dust/gas distribution models. We globally found the same reddening, $E(B-V) \sim 2.0$, and a similar distance, $D \sim 3.0$ kpc, with all the different models. This is consistent with previously reported values (Coleiro & Chaty 2013; Kaper et al. 2006). As the stellar radius was fixed to the most likely value found by Kaper et al. (2006), the distance is not totally constrained and may be slightly different than the values presented in Table 2.

The addition of a power law, used to model the free–free emission from the stellar wind around the HG and detected in radio by Pestalozzi et al. (2009), clearly improved the fits for all models. It thus seems likely that this component is required and has some contribution to the mid-infrared flux from the source. This contribution could even dominate the 70 $\mu$m flux (see Figures 5 and 6, right). Such a free–free emission component has been proposed by Kaper et al. (2006), but was ruled out by Kaplan et al. (2006) and thus required confirmation.

5.1. Structure of the CS Environment

The model components related to the infrared excess are indicative of the structure of the CS environment of GX 301–2.

We obtain a relatively good fit over five orders of magnitude in wavelength with the simplest model composed of the CK04 stellar photosphere model and a power law with index $\sim 0.75$ ...

### Table 2

| Model               | $D$ (pc) | $E(B-V)$ | $T_{\text{in}}$(K) | $R_{\text{in}}$ ($R_\odot$) | $R_{\text{out}}$ ($R_\odot$) | $T_{\text{out}}$ (K) | $\alpha$ | $\chi^2$/dof |
|---------------------|----------|----------|--------------------|-------------------------------|-----------------------------|---------------------|---------|-------------|
| Power law           | 2994 ± 54| 2.01 ± 0.04| ···                | ···                           | ···                         | 0.75 ± 0.01         | 23.0/13 |
| Sphere              | 2888 ± 62| 2.08 ± 0.06| 411 ± 47           | ···                           | 1288 ± 197                  | ···                 | 47.4/12 |
| Classical disk      | 2950 ± 48| 2.06 ± 0.04| 470 ± 69           | ···                           | 919 ± 169                   | ···                 | 25.9/12 |
| Rimmed disk         | 2784 ± 42| 2.05 ± 0.04| 1658 ± 127         | [70]                          | 4263 ± 1437                 | ···                 | 21.4/12 |
|                     | 2830 ± 42| 2.04 ± 0.04| 1711 ± 150         | [70]                          | 1785 ± 623                  | ···                 | 18.6/12 |
|                     | 2961 ± 95| 1.97 ± 0.05| 238 ± 35           | [70]                          | 4208 ± 802                  | 1837 ± 306          | 14.1/10 |
|                     | 3215 ± 405| 1.92 ± 0.09| 400 ± 95           | [70]                          | 1858 ± 339                  | 3267 ± 1672         | 8.4/10  |

**Notes.** The parameters reported here are defined in Section 3. The star temperature $T_s = 18,000$ K and radius $R_s = 70 R_\odot$ are fixed parameters. When other parameters are fixed, we indicate the value in brackets. $R_{\text{in}}$ is equal to $R_s$ and $H_{\text{in}}$ is fixed to 15 $R_\odot$ following Chaty & Rahoui (2012). The inclination is fixed to $i = 60^\circ$ (Kaper et al. 2006).

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**Figure 3.** SED of GX 301–2 (Wray 977) fitted with a stellar photosphere model and a power law to account for the infrared excess.

(A color version of this figure is available in the online journal.)
Figure 4. SED of Wray 977 (GX 301–2) fitted with a stellar photosphere model and a spherical blackbody component (left) and an additive power law to account for the stellar wind (right).

(A color version of this figure is available in the online journal.)

Figure 5. SED of Wray 977 (GX 301–2) fitted with a stellar photosphere model and a classical disk component (left) and an additive power law to account for the stellar wind (right).

(A color version of this figure is available in the online journal.)
Figure 6. SED of Wray 977 (GX 301–2) fitted with a stellar photosphere model and a rimmed disk component (left) and an additive power law to account for the stellar wind (right).

(A color version of this figure is available in the online journal.)

It thus seems that the infrared excess in the SED might be explained mostly by the stellar wind. However, there is a number of features that point toward more complex models. First, this simple model would contradict the idea that this highly obscured source hosts dust in its CS environment, as revealed by intrinsic silicate absorption lines and continuum emission excess in the infrared (see, e.g., Kaplan et al. 2006; Moon et al. 2007). The Herschel/PACS data point at 70 $\mu$m appears to be more than 3$\sigma$ away from the model, suggesting a curvature in the spectrum. Also, the curvature of the data in $JHK_s$ is not well followed by the model (see residuals in Figure 3). We thus cannot exclude a break in the mid-infrared with a change of index of the power-law slope or discontinuities as discussed in Wright & Barlow (1975). More data points would be required in order to better constrain the shape of the SED.

We thus give credit to more explicit models that are used to test the possible geometry of the CS gas/dust. The spherical distribution models lead to lower fit quality, though they cannot be completely ruled out. The fits of disk models returned relevant parameter values, though we note that degeneracies in the fits and a complex extended emission around the source might bring additional uncertainties on the absolute values reported here. The size of the dusty disks we derived is about 1800 $R_\odot$, (25 stellar radii, or 8 AU), which is comparable to the sizes derived by Lachaume et al. (2007) for the B[e] star Hen 3–1191 or derived through interferometry for similar objects (Millour et al. 2011). Compared to the dusty shells observed among most of LBVs (up to a few pc, Clark et al. 2003), the size is however much smaller. The low temperatures we obtained in the disk, which are close to 200 K at the outer edges of the disk, are well below the dust sublimation temperature, indicating that dust can indeed be formed in such a CS environment of GX 301–2.

The rimmed disk model is particularly instructive on the possible structure of the CS environment. It contains an irradiated rim at the inner edge of the disk that efficiently protects the disk from the ionizing radiation of the star. Following Lachaume et al. (2007), the rim radius $R_{\text{rim}}$ for a temperature close to the dust sublimation temperature is expected to be around 1400 $R_\odot$ for GX 301–2 in the large gap scenario (their Equation (2), valid for a rimmed disk with optically thin inner gas), which corresponds to the value obtained in our final fit (Figure 6, right). There is a clear degeneracy between $R_{\text{rim}}$ and $H_{\text{rim}}$ (the latter is fixed in the model). Therefore we cannot give clear constraints on the value of $R_{\text{rim}}$. In the small gap scenario (more similar to a classical disk with optically thick inner gas, see Lachaume et al. 2007), the radius at which the temperature equals the dust sublimation temperature is expected to be $\sim 400 R_\odot$. However, such temperatures are found at the inner edge of the classical disk in our modeling, close to the star surface (thus significantly below 400 $R_\odot$), arguing against the classical disk model.

For sgB[e] stars, it is generally agreed that a rimmed disk is present around the star, but strong [O I] emission lines
detected in their NIR spectra instead point toward a temperature between 5000 and 10,000 K for the rim (Kraus et al. 2007). In GX 301–2, there are no such lines and thus a rim at such a high temperature cannot be present. Therefore, the rimmed disk solution we obtained, with a rim temperature compatible with the dust sublimation temperature, appears to be plausible.

The size of the dusty disk structure is larger than the neutron star distance to the HG star in GX 301–2, estimated to be 100–200 $R_\odot$, so about twice the stellar radius (e.g., Kaper et al. 2006). The structure we observe here would thus surround the binary system. The possible presence of a gas stream close to the periastron of the orbit of the neutron star has been proposed to explain the evolution of the accretion rate, as seen in X-rays (Leahy 2002; Evangelista et al. 2010). Such a feature would not be directly connected, at least spatially, to the CS dusty disk.

5.2. Comparison with Similar Objects

Globally, the CS environment of GX 301–2 appears to be similar to the environment of the obscured HMXB IGR J16318–4848, hosting a sgB[e] companion star (Chaty & Rahoui 2012), and to sgB[e] stars in general. We thus strengthen the connections between the two systems, which may have undergone a similar evolution that led to the formation of a dense CS environment with a disk hosting dust. GX 301–2 has known orbital parameters, particularly a significant eccentricity, while there is no evidence for variability for IGR J16318–4848 and most probably a circular orbit. This difference might be due to a slightly different stage in the evolution after the SN that formed the neutron star or to a different initial mass or conditions in the system.

For another similar source, CI Cam, the geometry of the dusty envelope has been unambiguously determined with long baseline optical interferometry as a torus or a disk (of a few AU in radius), and the hypothesis of a spherical dust shell is totally ruled out (Thureau et al. 2009). The binary companion would also lie interior to the dusty disk. This structure is similar to the proposed rimmed disk model we tested for GX 301–2.

GX 301–2 has been reported to share common properties with 4U 1907+097, which is also a slow pulsar and a O8/O9 supergiant companion with a dense stellar wind (Cox et al. 2005). It seems to follow a similar evolution track. This system is a highly obscured HMXB and could be a missing link between supergiant fast X-ray transients and ordinary accreting pulsars (Doroshenko et al. 2012). It would be interesting to test the presence of surrounded dust around the system; however, its larger distance and high extinction make it more difficult to study.

More globally, IGR J16318–4848 is the prototype of a larger class of obscured X-ray binaries, and as such, this whole class of objects could represent a similar step in the evolution of massive stars in binary systems. The number of known supergiant HMXBs has dramatically increased over the last decade with new detections using INTEGRAL. For the HMXBs confirmed by spectral type, we now have 49% of Be HMXBs, 42% of supergiant HMXBs, and 9% of peculiar HMXBs (Coleiro et al. 2013), while we had only 4% of supergiant HMXBs before INTEGRAL. Obscured systems hosting a supergiant may be explained by ejections of matter during phases of interaction with the compact object (see, e.g., Kraus et al. 2010; Wheelwright et al. 2013). This scenario might be related to the formation of a dusty disk around those systems. More observations and modeling of their infrared excess, and possibly mapping of the CS environment through interferometry, would reveal and confirm the similarities of those objects and allow us to perform population studies.

5.3. Origin of the Dusty Disk

Assuming that a disk of material effectively surrounds GX 301–2, it might have initially formed through the bi-stability mechanism, a scenario proposed for sgB[e] stars (Lamers & Pauldrach 1991; Pauldrach & Puls 1990). This is strengthened by the fact that the surface effective temperature found for the HG star in GX 301–2 is close to 19,300 K and was probably higher before its evolution to the HG stage. With this mechanism, it is possible to get a density contrast of about 10 between the equator and the pole. Another scenario proposed for the formation of a disk in sgB[e] system requires a high rotational velocity, leading to the formation of an equatorial, wind-compressed disk (Bjorkman & Cassinelli 1993; Bjorkman 1999). This scenario might be complementary to the bi-stability mechanism, as shown by Pelupessy et al. (2000), in order to explain the formation of disks around sgB[e] with observed density contrast of a factor of ~100.

In addition to those processes, the presence of a nearby companion (the neutron star in GX 301–2), even when it is much less massive than the primary, could drastically affect a stellar wind. It was argued that the formation of a dusty disk could be directly due to the presence of a companion around the massive star and non-conservative mass transfer (Plets et al. 1995; Clark et al. 2013). Tidal interaction in the binary system could create high-density blobs, which would form a rim. This rim could then efficiently protect the disk from the stellar radiation and enable the formation of dust. The fact that we favor a rimmed disk model for GX 301–2 appears to give credit to this scenario. In the same way, some sgB[e] exhibit a disk and the most probable hypothesis is that the accumulation of matter in the equatorial plane is due to the presence of a low-mass companion (e.g., Millour et al. 2011, 2013).

5.4. Evolutionary Track

The evolution of the particular system GX 301–2 has been modeled by Wellstein & Langer (1999), who favored a scenario with an initial binary system of 25 and 26 $M_\odot$ that underwent conservative mass transfer. The associated transfer of angular momentum has led to the formation of one of the slowest known pulsars with a wide orbit. It also potentially spun up the HG star, possibly enabling or strengthening the mechanism of disk formation around the HG star. The possible evolution of the system has been modeled by Belczynski et al. (2012), as GX 301–2 is a potential progenitor for a black hole + neutron star binary, and thus is among the most promising gravitational wave sources. However, the expansion of the massive companion will be so rapid that the system will probably create a WR star and then end up with the neutron star sinking into the helium core of the companion star, i.e., a merger.

The disk-like structure of the dust around the HG in GX 301–2 is strikingly similar to the structure observed around supergiant stars showing the B[e] phenomenon (Lamers et al. 1998), suggesting a link between those two classes of objects. We also note that GX 301–2 (Wray 977) has similar properties to the group of LBV stars (Clark et al. 2012, 2013), also suggesting a connection between those classes. It thus appears that there are probably evolutionary links between the HG stage in GX 301–2, sgB[e] systems, LBVs, and obscured HMXBs.
Forbidden lines have been detected in GX 301–2 (Moon et al. 2007), though there are differences with the lines more commonly associated to the B[e] phenomenon. The inferred temperature for the radiation exciting the [Ne ii] and [Ne iii] lines is hotter than the stellar photospheres, so there can be some contribution from the illumination of hard X-rays from the central compact X-ray source (Moon et al. 2007). As [Ni ii] and [Fe ii] were detected only in IGR J16318−4848 (which contains a sgB[e]) while [Fe iii] was only in GX 301–2, this suggests the presence of a slightly harder radiation field in GX 301–2. One possibility is that the HG stage is similar to the sgB[e] stage for systems with a harder radiative field (e.g., hosting an X-ray source) or that are more massive initially. It is, however, more likely that the HG is an evolved sgB[e] (sgB[e] X-ray source) or that are more massive initially. It is, however, more likely that the HG is an evolved sgB[e] (sgB[e] X-ray source) or that are more massive initially. It is, however, more likely that the HG is an evolved sgB[e] (sgB[e] X-ray source) or that are more massive initially. It is, however, more likely that the HG is an evolved sgB[e] (sgB[e] X-ray source) or that are more massive initially. It is, however, more likely that the HG is an evolved sgB[e] (sgB[e] X-ray source) or that are more massive initially. It is, however, more likely that the HG is an evolved sgB[e] (sgB[e] X-ray source) or that are more massive initially. It is, however, more likely that the HG is an evolved sgB[e] (sgB[e] X-ray source) or that are more massive initially. It is, however, more likely that the HG is an evolved sgB[e] (sgB[e] X-ray source) or that are more massive initially. It is, however, more likely that the HG is an evolved sgB[e] (sgB[e] X-ray source) or that are more massive initially. 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GX 301–2 might represent a peculiar and short-lived stage in the evolution of massive stars in binary systems that could be represented by the following steps:

\[ \text{sgB[e]} \rightarrow \text{HG} \rightarrow \text{LBV} \rightarrow \text{WR} \rightarrow \text{SN}. \]

This track might be specific to binary systems that become X-ray binaries with an accreting compact object during their evolution and can be seen as highly obscured X-ray binaries at one point.

6. CONCLUSIONS

We modeled the optical to radio SED of GX 301–2 and found relatively good fits with different models, all containing a spherical photosphere and a power law representing the stellar wind. These two components could be sufficient to explain the emission, though they do not explain the presence of dust as reported in previous work. Models including a spherical or disk-like distribution of material can also reproduce the SED. Through comparisons with similar objects, the spherical and classical disk distributions seem less likely to be present in GX 301–2. The rimmed disk model shows acceptable parameters and relates to viable mechanisms that would explain the evolution of the system as well as strengthen the connections to other categories of massive stars such as LBVs and sgB[e].

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