The complete submillimetre spectrum of NGC 891

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ABSTRACT

Submillimetre maps of NGC 891 have been obtained with the PRONAOS balloon-borne telescope and with the ISOPHOT instrument on board the ISO satellite. In this article, we also gather data from IRAS and SCUBA to present the complete submillimetre spectrum of this nearby edge-on spiral galaxy. We derive submillimetre emission profiles along the major axis. The modified blackbody fits, assuming a single dust component, lead to temperatures of 19-24 K toward the centre and 18-20 K toward the edges, with possible variations of the dust spectral index from 1.4 to 2. The two-component fits lead to a warm component temperature of 29 K all along the galaxy with a cold component at 16 K. The interstellar medium masses derived by these two methods are quite different: 4.6×10^9 M☉ in the case of the one-component model and 12×10^9 M☉ in the case of the two-component one. This two-component fit indicates that the cold dust to warm dust ratio is 20 to 40, the highest values being in the wings of this galaxy. Comparing to dust mass estimates, both estimations of the ISM mass are consistent with a gas to dust mass ratio of 240, which is close to the Milky Way value. Our results illustrate the importance of accurate submillimetre spectra to derive masses of the interstellar medium in galaxies.

Key words: dust, extinction – galaxies: individual (NGC 891) – galaxies: ISM – galaxies: spiral – galaxies: structure – infrared: galaxies.

1 INTRODUCTION

NGC 891 is one of the most perfect edge-on (Sofue & Nakai 1993) spiral galaxies in our neighbourhood. This peculiarity, and its similarity with the Milky Way galaxy in Hubble type (Sb), optical luminosity and rotational velocity (van der Kruit 1984), has allowed it to be intensively studied in order to understand the distribution and the characteristics of the galactic interstellar medium. It has been widely studied in radio continuum (e.g. Allen et al. 1978, Dahlem et al. 1994), carbon monoxide (García-Burillo et al. 1992, Scoville et al. 1993, Sofue & Nakai 1993, García-Burillo & Guélin 1995, Sakamoto et al. 1997), atomic hydrogen (for instance Swaters et al. 1997), molecular hydrogen (Valentijn & van der Werf 1999) and optical extinction (Howk & Savage 1997). The dust far-infrared continuum emission has been observed by the IRAS satellite (Wainscoat et al. 1997, Rice et al. 1988), the 1.3 mm emission by Guélin et al. (1993), and the submillimetre emission has recently been mapped with SCUBA at 450 and 850 µm by Alton et al. (1998) and Israel et al. (1999). For instance, Alton et al. (1998) showed that the dust submillimetre emission could be fitted by a two-dust component model, assuming a spectral index equal to 2. However, this was a fit with zero degree of freedom, thus it needs to be confirmed by including other submillimetre measurements. The accurate knowledge of dust properties in this galaxy, and therefore in other spiral galaxies such as the Milky Way, needs a better submillimetre spectral coverage, in order to properly derive the dust temperature(s) and spectral index. This is crucial to derive accurate masses of the interstellar medium in galaxies.

In this article, we present new results obtained in the submillimetre range with the ISOPHOT (Lemke et al. 1996) instrument on board of ESA’s Infrared Space Observatory (Kessler et al. 1996), and with the PRONAOS (PRogramme NAtional d’Observations Submillimétriques) balloon-borne telescope. Section 2 presents the observations and data processing, Section 3 presents the results obtained, and Section 4 presents an analysis of the data set.

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2 OBSERVATIONS AND DATA PROCESSING

2.1 PRONAOS data

PRONAOS is a French balloon-borne submillimetre experiment. Four bolometers cooled at 0.3 K measure the submillimetre flux with sensitivity to low brightness gradients of about 4 MJy/sr in band 1 (200 μm) and 0.8 MJy/sr in band 4 (580 μm). The effective wavelengths are 200, 260, 360 and 580 μm, and the angular resolutions are 2′ in bands 1 and 2, 2.5′ in band 3 and 3.5′ in band 4. Details about the instrument can be found in Ristorcelli et al. (1998) and Lamarre et al. (1994). The data which we analyze here were obtained during the second flight of PRONAOS in September 1996, at Fort Sumner, New Mexico. The data processing and the map-making method, including deconvolution from chopped data, are described in Dupac et al. (2001). However, for these NGC 891 data, we use a non prior deconvolution method, implemented the same way as the Wiener filter in Dupac et al. (2001). Indeed, these data are quite noisy, so the optimal Wiener filter may somehow modify the signal, which is not the case with the non prior map-making method. Then we carefully subtract the background around the galaxy to get the corrected surface brightness, and we smooth the maps of the first three bands with adequate profiles in order to obtain the same angular resolution as the fourth band (3.5′). After having done this, we check the correlation of the pixels in each band with respect to all the other bands in order to detect possible residual offsets between bands. This happened in band 2 that we rescaled to match the other bands. The noise fluctuations in the final maps define the spatial relative uncertainty which is 5 MJy/sr at 200 μm, 4 MJy/sr at 260 μm and 2 MJy/sr at 360 and 580 μm. The intercalibration error between bands is 5 % (1 σ), and the absolute calibration uncertainty is 8 %.

2.2 ISOPHOT data

NGC 891 has been mapped with ISOPHOT using the Astronomical Observation Template PHT32 in chopped mapping mode with the C200 array detector (2×2 pixels, 92'' per pixel) at the reference wavelengths 170 and 200 μm (see details in Laureijs et al. 2001). The data have been processed using the ISOPHOT Interactive Analysis software PIA v9.1 (Gabriel et al. 1997). The data reduction procedure includes ramp linearisation, ramp deglitching, reset interval correction, dark current subtraction, signal linearisation and signal deglitching. Each observation has been bracketted with two measurements of the fine calibration source (FCS). For the flux calibration, we have used the second FCS. The first quartile normalisation flat-fielding method has been used as implemented in PIA in order to correct for the remaining responsivity differences of the individual detector pixels. We smooth the derived 1.5′-resolution maps to 3.5′ in order to obtain a consistent data set. The absolute photometric error of ISOPHOT is around 20 %.

2.3 IRAS and SCUBA data

We use the SCUBA 450 and 850 μm flux profiles, as well as the high resolution (HiRes) 60 and 100 μm flux profiles from the InfraRed Astronomical Satellite survey, as published in the InfraRed Astronomical Satellite survey, as published in Laureijs et al. (2001). The data have been processed using the ISOPHOT Interactive Analysis software PIA v9.1. The data which we analyze here were obtained during the second flight of PRONAOS in September 1996, at Fort Sumner, New Mexico. The data processing and the map-making method, including deconvolution from chopped data, are described in Dupac et al. (2001). However, for these NGC 891 data, we use a non prior deconvolution method, implemented the same way as the Wiener filter in Dupac et al. (2001). Indeed, these data are quite noisy, so the optimal Wiener filter may somehow modify the signal, which is not the case with the non prior map-making method. Then we carefully subtract the background around the galaxy to get the corrected surface brightness, and we smooth the maps of the first three bands with adequate profiles in order to obtain the same angular resolution as the fourth band (3.5′). After having done this, we check the correlation of the pixels in each band with respect to all the other bands in order to detect possible residual offsets between bands. This happened in band 2 that we rescaled to match the other bands. The noise fluctuations in the final maps define the spatial relative uncertainty which is 5 MJy/sr at 200 μm, 4 MJy/sr at 260 μm and 2 MJy/sr at 360 and 580 μm. The intercalibration error between bands is 5 % (1 σ), and the absolute calibration uncertainty is 8 %.

Figure 1. Major axis intensity profiles of NGC 891 obtained with ISOPHOT and PRONAOS. The 170 and 200 μm ISOPHOT profiles are respectively presented as a dashed line and a long-dashed line. The angular resolution of these profiles is 1.5′. The 200, 260, 360 and 580 μm PRONAOS profiles are respectively plotted as a full line, a dotted line, a dash-dotted line and a dash-dot-dotted line. The angular resolution is 2′ in the first two bands, 2.5′ in the third and 3.5′ in the fourth.

Alton et al. (1998). We smooth the original profiles to the angular resolution of the fourth band of PRONAOS (3.5′).

3 RESULTS

The information obtained is presented as intensity profiles along the major axis in Fig. 1. We have checked the photometry of all 3.5′-resolution maps with respect to all the others, by plotting pixel-pixel diagrams. No noise offset between bands could be detected. In particular, both 200 μm bands (ISOPHOT and PRONAOS) are in good agreement with each other, which gives a good global consistency to the data set.

All bands of PRONAOS and ISOPHOT show a good symmetry between both sides of the galaxy, which extends approximatively 4′ away from the centre. This extension is similar to the one of the SCUBA maps of Alton et al. (1998) and Israel et al. (1999). Fig. 1 shows a large enhancement of the intensities at an angular distance of about 1.5′ away from the galactic centre along the north-eastern side of the galaxy. This is clearly visible in the 200 and 260 μm PRONAOS bands which have the adequate angular resolution (2′), as well as in both ISOPHOT bands. This enhancement can also be seen (at the same place) in the SCUBA maps presented by Alton et al. (1998) and Israel et al. (1999). Another enhancement, though less large, is visible at the same angular distance on the other side of the galaxy on SCUBA maps. The explanation for these enhancements could be spiral arms or a molecular ring encircling the galactic bulge.
4 ANALYSIS

4.1 The dust submillimetre emission

We present in Fig. 2 the spectra obtained towards the galactic centre and 3′ away from the centre on either side. The plotted error bars are dominated by the global calibration uncertainty of each instrument. As can be seen in Fig. 2, the submillimetre spectral energy density is very well constrained with the present data.

Several fitting procedures have been applied to the three spectra displayed in Fig. 2. The usual simple modelization of the large-grain emission is the modified blackbody, which obeys the following equation:

\[ I_\nu = \epsilon_0 \, B_\nu(\lambda, T) \left( \frac{\lambda}{\lambda_0} \right)^{-\beta} \] (1)

where \( \lambda \) is the wavelength, \( \epsilon_0 \) the emissivity of the observed dust column density at \( \lambda_0 \), \( T \) the temperature of the grains, \( \beta \) the spectral index and \( B_\nu \) the Planck function.

We fit the data using a one-component modified blackbody model, with and without the 60 \( \mu \)m point (which may be contaminated by very small grain emission, see Désert et al. 1990) and assuming \( \beta=2 \) or not. We also fit the data using a two-component model, assuming \( \beta=2 \) for both components, which have different temperatures. A summary of the results is shown in Table 1.

The derived parameters (temperatures and spectral indices) are consistent for the three fitted positions (centre, north-east and south-west). However, the central peak exhibits a slightly higher temperature than the wings. This is also true for the two-component fits and the fits with the 60 \( \mu \)m data. The one-component fits with \( \beta \) free and without the 60 \( \mu \)m data show that the wings may have a spectral index slightly lower than 2, while the centre exhibits a low spectral index (1.4). The results show an anticorrelation between the temperature and the spectral index, which is consistent with previous results obtained by Dupac et al. (2001), Dupac et al. (2002) and Dupac et al. (2003). However, if one considers \( \beta=2 \) to be the rule, then the central peak still exhibits a higher temperature (19 K) than the wings (18 K). This is less than what derived by Israel et al. (1999) under the same assumption of \( \beta=2 \), with IRAS 100 \( \mu \)m and SCUBA data only (21 K). Fitting two dust components to the emission longwards of 100 \( \mu \)m does not give very significant results: the warm temperature is not much changed with respect to the one-component fit (\( \beta=2 \)) temperature, and the cold component is indeed extremely cold (5-9 K). Therefore, and given the goodnesses of fit presented in Table 1, we consider that the dust emission longwards of 100 \( \mu \)m is very adequately fitted by a single dust population.

The fits including the 60 \( \mu \)m emission show that the one-component modeling is still possible, especially toward the centre where the \( \chi^2 / \text{d.o.f.} \) value is low for the fit with \( \beta \) free. In this case, the derived spectral indices are low: 1.15 toward the central peak and around 1.4 toward the wings. However, the \( \chi^2 / \text{d.o.f.} \) values are clearly larger than those of the fits longwards of 100 \( \mu \)m. This may indicate that a two-component model is useful for fitting with the 60 \( \mu \)m emission. This fit gives temperatures of 29 and 16 K, as well for the wings as for the centre. Given this quite high temperature of 29 K, it is likely that the 60 \( \mu \)m emission...
the major axis, which corresponds to 25 kpc. For estimating the mass of the galactic interstellar medium, we follow the simple model described in Dupac et al. (2001), which uses the dust 100 \( \mu m \) opacity in the diffuse interstellar medium from Désert et al. (1990). In this model, the total column density of interstellar medium is simply proportional to \( \epsilon_{100} \), the coefficient being \( 1.67 \times 10^{24} \) H cm\(^{-2}\). Two mass estimations are made: one assumes a single dust component with the emissivity \( \epsilon_{100} \) varying along the major axis as derived by the \( \beta \)-free fits without the 60 \( \mu m \) data (see Table 1); the other assumes two dust components with varying emissivities as derived by the two-component fits with the 60 \( \mu m \) data. In either case, we assume a distance to NGC 891 of 9.5 Mpc (van der Kruit & Searle 1981). We find a mass of the interstellar medium of \( 4.6 \times 10^9 \) M\(_\odot\) when applying the one-component free-\( \beta \) model, whereas we find \( 12 \times 10^9 \) M\(_\odot\) when applying the two-component model (including the 60 \( \mu m \) points). This discrepancy is due to the existence of quite large amounts of cold (15.7 K) dust in the two-component results. The value of \( 4.6 \times 10^9 \) M\(_\odot\) is consistent with previous estimates from Guélin et al. (1993): \( 4 \times 10^9 \) M\(_\odot\), and Israel et al. (1999): \( 3.9 \times 10^9 \) M\(_\odot\). We can assume from Guélin et al. (1993) that the atomic hydrogen mass is \( 2.5 \times 10^9 \) M\(_\odot\), which gives a molecular hydrogen amount of \( 2.1 \times 10^9 \) M\(_\odot\) from our measurement (one-component fit). This is in good agreement with the standard assumption of similar quantities of atomic and molecular gas in spiral galaxies. However, if we trust the two-component estimation, the molecular to atomic gas ratio becomes 3.8, which is much larger than standard assumptions. This amount of molecular gas \((9.5 \times 10^9 \text{ M}_\odot)\) is not in good agreement with the standard estimation from CO measurements either, using the CO-to-\( H_2 \) conversion factor of Strong et al. (1988): \( 4.5 \times 10^9 \) M\(_\odot\). From this two-component modeling, we derive cold-over-warm component mass ratios for the three studied positions: 19 for the centre, 42 for the north-eastern data point and 34 for the south-western one. Therefore, there is a strong trend to consider that the cold (16 K) dust amount is much larger than the warm dust amount, and that the cold to warm dust ratio is twice larger in the wings of this galaxy than in the centre. These ratios are smaller than those derived by Alton et al. (1998) with IRAS and SCUBA data only, but larger than those derived by Israel et al. (1999) with slightly different temperatures (cold to warm dust ratio of about 10).

As our ISOPHOT and PRONAOS measurements constrain very well the peak of the spectra, we are confident in the reliability of the derived dust properties (emissivity, temperature and spectral index). However, the different possibilities to fit (well) the spectra lead to different estimates of the mass. If one accepts the possibility that the spectral index of the dust can be somewhat different from 2, which seems wise to us regarding recent results (Walker et al. 1990, Ristorcelli et al. 1998, Dupac et al. 2001, Dupac et al. 2002, Dupac et al. 2003, Bennett et al. 2003), it does not seem possible to better discriminate between the different fitting procedures given the present data, although the spectral coverage is relatively accurate. Also, the \( \epsilon/\text{N}_H \) ratio used (Désert et al. 1990) is debatable, and the mass estimates are of course very much dependent on this value.

We compare these ISM mass estimates to the dust mass \((19 \times 10^9 \text{ M}_\odot)\) of NGC 891 obtained by Alton et al. (2000),

### Table 1. Results of the fits toward the centre of the galaxy and 3\( \prime \) away along the major axis on either side (north-east and south-west), for the different methods investigated. d.o.f. stands for degrees of freedom.

| Component | \( \beta \) free, without 60 \( \mu m \) | \( \beta \) = 2, without 60 \( \mu m \) |
|-----------|---------------------------------|---------------------------------|
| One       |                                 |                                 |
| T (K)     | \( \beta \)                      | \( \chi^2/\text{d.o.f.} \)      |
| Centre    | 23.5 ± 2.6                      | 1.41 ± 0.23                     | 0.31/6 |
| N-E       | 19.6 ± 1.8                      | 1.70 ± 0.25                     | 0.66/6 |
| S-W       | 18.1 ± 1.6                      | 1.96 ± 0.29                     | 1.51/6 |
| Two       |                                 |                                 |
| Components, \( \beta \) = 2, without 60 \( \mu m \) |                                 |
| T\(_{\text{warm}}\) (K) | \( \beta \) | \( \chi^2/\text{d.o.f.} \) |
| Centre    | 21.0\(_{+3.4}^{-3.4}\)          | 9.6\(_{+13.8}^{-13.8}\)         | 1.94/5 |
| N-E       | 18.3\(_{+2.6}^{-2.6}\)          | 7.7\(_{+13.1}^{-13.1}\)         | 3.86/5 |
| S-W       | 18.3\(_{+1.8}^{-1.8}\)          | 5.0\(_{+14.8}^{-14.8}\)         | 8.43/5 |

### Table 2. Instrument, wavelength (\( \mu m \)), total flux density integrated over three 3\( \prime \) beams (25 kpc) along the major axis.

| Instrument | Wavelength (\( \mu m \)) | Total Flux Density (Jy) |
|------------|--------------------------|-------------------------|
| IRAS/HiRes | 60                       | 50.5 Jy                  |
| IRAS/HiRes | 100                      | 126 Jy                   |
| ISO        | 170                      | 197 ± 21 Jy              |
| ISO        | 200                      | 144 ± 17 Jy              |
| PRONAOS    | 200                      | 161 ± 10 Jy              |
| PRONAOS    | 260                      | 120 ± 8 Jy               |
| PRONAOS    | 360                      | 50 ± 4 Jy                |
| SCUBA      | 450                      | 32.0 Jy                  |
| SCUBA      | 580                      | 19 ± 3 Jy                |
| SCUBA      | 850                      | 4.62 Jy                  |
assuming given values for the grain radius and density. This is substantially less than the estimation of $50 \times 10^6 M_\odot$ from Alton et al. (1998), who used a two-component model of the submillimetre emission. Comparing the Alton et al. (2000) dust mass to our ISM mass estimates, we obtain a gas to dust mass ratio of 240 for the one-component mass estimate and 640 for the two-component one. The first estimate of this ratio is slightly less than that derived by Alton et al. (2000): 260, a bit closer to the Milky Way value and well in agreement with the canonical dependence on the metallicity (Issa et al. 1990). If we compare the ISM mass estimate from our two-component model ($12 \times 10^6 M_\odot$) to the two-component model estimate from Alton et al. (1998): $50 \times 10^6 M_\odot$, then the gas to dust ratio is (also) 240. We therefore consider that this value is somewhat robust.

5 CONCLUSION

We have presented PRONAOS and ISOPHOT data of the NGC 891 spiral galaxy, together with IRAS and SCUBA measurements. The overall submillimetre spectrum of this object is now well constrained, and two different conclusions can be derived: either one single dust component is fitted to the spectra (without the 60 $\mu$m data), and in this case the temperature is higher toward the centre of the galaxy than toward the wings, and the spectral index is less steep ($1.4 \pm 0.3$ in the centre and 1.7-2 in the wings); either two components are fitted assuming $\beta=2$, and this leads to a warm temperature of 29 K and a cold temperature of 16 K. The interstellar medium masses derived by these two methods are quite different, but both are consistent with a gas to dust mass ratio of 240.

The good spectral coverage of the submillimetre range that we present here makes us rather confident in our determination of the dust emission properties. However, the way to fit the data, as well as the opacity properties, lead to inevitable uncertainties in the determination of the masses. A next step in the accurate knowledge of the continuum emission of this galaxy, as well as of other nearby spirals, would be to obtain the same spectral resolution in the same wavelength range with a better angular resolution. This should allow to better discriminate the number of distinct components, as well as the possible variations of the spectral index, and this should be achieved by forthcoming experiments such as the Herschel satellite with the instruments PACS (Poglitsch et al. 2001) and SPIRE (Griffin et al. 2001).

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