SCUBA imaging of NGC 7331 dust ring

S. Bianchi, 1 P. B. Alton, 1 J. I. Davies 1 and M. Trewhella 2

1 Department of Physics and Astronomy, University of Wales Cardiff, P.O. Box 913, Cardiff, CF2 3YB, UK
2 IPAC, M.S. 100-22 Caltech, Pasadena, CA91125, USA

ABSTRACT
We present observations of the spiral galaxy NGC 7331 using the Sub-millimetre Common User Bolometer Array (SCUBA) on the James Clark Maxwell Telescope. We have detected a dust ring of 45 arcsec radius (3.3 kpc) at wavelengths of 450 and 850-µm. The dust ring is in good correspondence with other observations of the ring in the mid-infrared (MIR), CO and radio-continuum, suggesting that the observed dust is associated with the molecular gas and star formation. A B-K colour map shows an analogous ring structure with an asymmetry about the major axis, consistent with the extinction being produced by a dust ring. The derived temperature of the dust lies between 16 and 31 K and the gas-to-dust ratio between 150 and 570, depending on the assumed dust emission efficiency index (β = 1.5 or 2).

Key words: galaxies: individual: NGC 7331 – galaxies: ISM – galaxies: structure – dust, extinction

1 INTRODUCTION
Modelling of COBE-DIRBE observation of our Galaxy has shown that dust at T < 22 K associated with neutral and molecular gas is responsible for most of the emission (55-85 per cent) in the far-infrared (FIR) (Sodroski et al. 1994; Sodroski et al. 1997). Reach et al. (1997), analysing COBE-FIRAS spectral data, find that Galactic emission between 100-µm and 300-µm is predominantly from dust at T=16-23 K. This range of temperatures is in agreement with theoretical calculations for classical grains heated by the interstellar radiation field (ISRF) (Disney, Davies & Phillipps 1989).

In external galaxies, dust temperatures have been mainly measured using IRAS fluxes at 60-µm and 100-µm. IRAS can only trace warm dust at T ≥ 30 K (Devereux & Young 1990). This is mainly associated with star forming regions, as illustrated by the strong correlation between Ho and IRAS-FIR emission (Devereux 1993). Gas-to-dust ratios derived from IRAS are a factor of 10 larger than the Galactic value (Devereux & Young 1990). Assuming that the Galaxy is typical of spirals, the discrepancy can be explained by a colder dust component (T ≈ 15 K) that contributes to the bulk of the mass, without adding a lot of flux in the window observed by IRAS (Devereux & Young 1990). This is because of the strong dependence of emission on temperature (∝ T 4+β, β = 1 − 2).

Estimates of the temperature of the main dust component depend on the availability of data at λ > 100-µm. Recently, Alton et al. (1998a) have measured a (T) ≈ 20 K for a sample of 7 spiral galaxies, using ISPOT 200-µm maps combined with HiRes IRAS maps at 100-µm, 10K lower than the temperatures measured using IRAS HiRes 60-µm data. The mean gas-to-dust ratio is then ≈ 230, closer to the canonical Galactic value of 160 (Sodroski et al. 1994). Newly available FIR maps, despite their low resolution (117 arcsec for ISPOT data) have revealed that the spatial distribution of dust is more extended than that of the IRAS and K-band (stellar) emission (Alton et al. 1998a; Davies et al. 1998).

In this letter we describe sub-millimetre (submm) observations of NGC 7331 with SCUBA. Maps produced by SCUBA have a far higher resolution than ISPOT and HIRES IRAS long wavelength observations and give us detailed spatial information about the extent of cold dust. NGC 7331 is an Sb galaxy (de Vaucouleurs et al. 1991) at a distance of 15.1 Mpc (Hughes et al. 1998), giving an apparent scale of 73 pc arcsec⁻¹.

NGC 7331 shows a ring structure in CO emission (Tosaki & Shioya 1997; von Linden et al. 1996; Young & Scoville 1984), in radio-continuum (Cowan, Romanishin & Branch 1994) and in MIR images from ISOCAM (6.75-µm < λ < 15-µm) (Smith 1998). Smith (1998) also shows that these observations are in good correspondence with each other, indicating the presence of a molecular and dust ring of...
radius \approx 45 \text{ arcsec} (3 \text{kpc}). There is also a good match with H\alpha+[NII] features (Pogge 1989). The central region (radius \approx 2 \text{ arcmin}) is partially depleted of neutral hydrogen (Bosma 1981) while the molecular gas contributes to 70 per cent of the total gas mass inside the optical radius (Devereux & Young 1990). A major axis profile at 100-\mu\text{m} obtained with the Kuiper Airborne Observatory (KAO) (Smith & Harvey 1990) shows a flat-topped FIR distribution, but very little structure can be seen in the HiRes-IRAS maps or in the 200-\mu\text{m} ISOPHOT observations of Alton et al. (1998) (FWHM \gtrsim 35 \text{ arcsec}).

The ring may be the result of long-term dynamical evolution driven by a bar instability, as proposed by von Linden et al. (1996). Tosaki & Shioya (1997) relate the ring to the post starburst status of the galaxy: the central gas is consumed in the long evolution after the starburst event.

2 OBSERVATION AND DATA REDUCTION

NGC 7331 was observed at JCMT with SCUBA on 1997 October 20, 22, 24. SCUBA consists of two bolometer arrays able to simultaneously image a region of sky of about 2.3 arcmin in diameter: the short-wavelength array, optimised for observing at 450-\mu\text{m} (91 elements) and the long-wavelength array optimised at 850-\mu\text{m} (37 elements). To fully sample the field of view with both the arrays, the secondary mirror is moved in a 64-point jiggle pattern. For each jiggle position the integration time is 1 s. Simultaneously, the secondary mirror is also chopping with a frequency of 7 Hz to remove the sky background. Every 16 steps of the jiggle pattern, the telescope nods, to remove slowly varying atmospheric gradients. We used a chop throw of 180 arcsec perpendicular to the major axis of NGC 7331.

We frequently determined the transparency of the atmosphere during each night by measuring sky emission at several elevations. Sky conditions were stable during most of the observing run with zenith optical depths of \tau_{\alpha z} = 0.6 \pm 0.7 and \tau_{\alpha z} = 0.13 \pm 0.15. During the first night atmospheric opacity was higher, with \tau_{\alpha z} > 3 and \tau_{\alpha z} = 0.5. The telescope pointing was checked every hour against a bright point source close to our target: rms pointing errors were \approx 3 \text{ arcsec} in both azimuth and elevation. Several images of Uranus were taken for photometric calibration.

Data reduction was carried out using the STARLINK package SURF (Jenness & Lightfoot 1997; Sandell 1997). After subtracting the off-source signal, images were flat-fielded and corrected for atmospheric extinction. Noisy bolometers were masked. Each image was corrected for systematic noise variations using stable bolometers that appeared free of source emission. Spikes from transient detections were removed by applying a 3\sigma clip.

A calibration constant for each night was computed from the Uranus maps. Comparing data for each night we derived a relative error in calibration of 14 per cent and 7 per cent, for 450-\mu\text{m} and 850-\mu\text{m} respectively. Uranus images were also used to measure the beam size and the contribution of side lobes. The measured HPBW is 10 arcsec at 450-\mu\text{m} and 15 arcsec for 850-\mu\text{m}. The side lobes can introduce quite large systematic errors: for example, 20 per cent of the emission of a point source goes in the side lobes for the long wavelength and 60 per cent for the short wavelength.

In the following, values of integrated flux are corrected for the side-lobe pickup.

A total of 15 images at 450-\mu\text{m} and 19 at 850-\mu\text{m} were re-sampled to an equatorial reference frame, using pixels of 3 and 5 arcsec, respectively. The final map covers an area of 3.3 arcmin x 5.8 arcmin. The total on-source integration time for the central part of the image is 5700s and 8300s. Maps are shown in Fig. 2 contours with S/N \geq 3 are over-plotted. The short wavelength image clearly shows a poorer signal to noise, mainly due to the higher emissivity of the sky at 450-\mu\text{m} compared to 850-\mu\text{m}: the sky noise is 80 mJy beam^{-1} at 450-\mu\text{m} and 8 mJy beam^{-1} at 850-\mu\text{m}.

In this work we have also used B and K-band observations. Images were obtained from the Skinakas observatory Crete (B) and at the Wyoming Infrared Observatory (K). The optical and NIR data were reduced and calibrated in the standard way (Trewella 1997). The PSF has a FWHM=1.5 arcsec for the B-band image and 2.5 arcsec for the K-band. Optical images were aligned in a RA/Dec frame using field stars in the HST guide star catalogue. The peak emission in B-band image occurs at RA=22^{h} 37^{m} 0^{s}, Dec=+34^{d} 24^{m} 55^{s} (J2000); these coordinates are within 1.5 arcsec of the optical and radio emission centres given by Cowan et al. (1994). SCUBA images were aligned by assuming the B peak as the centre of the frame. Images in B-band and B-K colour are shown in Fig. 3. The B-K colour image has a photometric accuracy of 0.2 mag.

3 RESULTS & DISCUSSION

Our 850-\mu\text{m} image (Fig. 4 top-right) clearly shows a ring structure, of \approx 90 \text{ arcsec} x 30 \text{ arcsec} (radius \approx 45 \text{ arcsec}, corresponding to 3.3 kpc). This submm ring matches MIR observations, and therefore CO, radio-continuum and H\alpha+[NII], as shown in Smith (1998).

The brightest parts of the ring are on the north and south sides, where intensity peaks at almost the same value (95 mJy beam^{-1}, S/N \approx 12). The east and west side of the ring are less bright and appear clumpy. As suggested by von Linden et al. (1996) for the CO ring, this morphology may well be due to the inclined view. There are also two smaller structures attached to the north and south sources (shown in our image at positions [5,60] and [20,50], respectively). The south one, the brightest, is associated with the origin of one of the spiral arms in our optical image (Fig. 4 bottom-left). There is no evidence for a central source, contrary to the MIR images (Smith 1998). The ring is also visible in the 450-\mu\text{m} image (Fig. 4 top-left) despite the poorer signal. When smoothed to the long wavelength resolution, the same structures can be seen.

Radial surface-brightness profiles were produced for the 850-\mu\text{m} and the smoothed 450-\mu\text{m} images, averaging over elliptic annuli. We have adopted a disk inclination of 74^\circ and PA = 167^\circ (Garcia-Gomez & Athanassoula 1991). The two profiles can be followed out to 150 arcsec from the centre (both images with S/N > 1), and they appear similar (Fig. 5).

Using this last aperture, we have computed the integrated fluxes: we obtain a flux of 13.4 Jy for 450-\mu\text{m} and 1.9 Jy for 850-\mu\text{m}. The ratio between the fluxes is therefore 7.0 \pm 1.0, where the error is mostly due to the uncertainties.
in the calibration. From this ratio the average dust temperature can be computed, if the dependence of dust emissivity $Q_{em}$ on wavelength $\lambda$ is known. It is generally assumed that $Q_{em} \propto \lambda^{-\beta}$, with $\beta$ increasing from 1 to 2 going from the MIR to the FIR and submm (Hildebrand 1983). Fits of the Galactic FIR-submm spectrum (Reach et al. 1995) suggest a value $\beta = 2$ for $\lambda > 200$-µm. Millimetre/submm observations of the Galactic plane and cirrus (Masi et al. 1995) emissions are better described by $\beta = 1.5$. Using $\beta = 2$ we derive $T = 16\pm3$ K ($T = 31\pm10$ K for $\beta = 1.5$). The temperature obtained using $\beta = 2$ agrees very well with values for high latitude dust emission in the Galaxy (Reach et al. 1995). It is interesting to note that a grey-body model with $\beta = 1$ cannot be fitted to the data. This is also confirmed by SCUBA observations of NGC891 (Alton et al. 1998b).

The dust temperature was also derived using the KAO 100-µm observations presented by Smith & Harvey (1996). The image at 850-µm was smoothed to the KAO resolution (31 arcsec x 41 arcsec) and a profile along the major axis was produced, with the same orientation as the one shown in their Fig. 5. In the central 100 arcsec, where the KAO profile appears flat, the average flux density per bolometer at 100 µm is 29 Jy. In the same region the average value for the 850-µm flux is 60 mJy beam$^{-1}$. From the ratio we...
derived $T = 23\pm 2$ for $\beta = 2$ ($T = 29\pm 3$ for $\beta = 1.5$). Alton et al. (1998a) fluxes at 100-µm and ISO 200-µm give values $T = 17K$ for $\beta = 2$ and $T = 19K$ for $\beta = 1.5$.

The correspondence between the submm ring and other observations suggests that the dust emission is associated with the molecular gas. Indeed, the values of dust temperature we have presented here are consistent with those of the dust component associated with the molecular gas in the Galaxy (Sodroski et al. 1997).

The B-K map is shown in Fig. 1, bottom-right, with the 850-µm contour superimposed. A ring structure can be seen in the colour image, in excellent correspondence with the submm image. The ring is delimited on the east and the west side by regions with a redder colour with respect to the central one. The colour on the west side is also redder than on the east. The asymmetry and the central gap, first observed in NIR colors by Telesco, Gatley & Steward (1982), can be explained with a bulge obscured by an inclined dust ring: on the west side, the closer one, most of the bulge is behind the dust ring so that bulge light is more extinguished and therefore redder than on the east side, the far one. Because of the relative lack of dust in the middle of the structure, bulge light from the central region appears bluer.

To compare B-K with 850-µm emission, the colour image was smoothed to a resolution of 15 arcsec and rebinned on 5 arcsec pixels. We have then plotted B-K vs 850-µm for each pixel in an elliptic region of $\approx 100$ arcsec x 50 arcsec (Fig. 2). A clear trend is evident: for the same 850-µm flux, the closer part of the galaxy is systematically redder than the far one, by 0.5 mag. This is true both for the regions with high flux (i.e. high dust column density) that define the ring and for regions external to the ring. Bulge light extinguished by a more extended dust disk may be the reason for the colour asymmetry of these outer regions. As a check, we repeated the correlation using pixels of 15 arcsec, but the conclusions are the same: our results are thus independent of a possible misalignment of the colour and submm images, which we estimate to be at most 2.5 arcsec.

B-K is more sensitive than optical colours to the presence of dust (Block et al. 1994), because of the high ratio between extinction in B and K-band ($\approx 14$, using a Galactic extinction law (Whittet 1992)). Even so, deriving the dust content from the colour image is quite difficult: first an a priori knowledge of the intrinsic colour distribution is required, to quantify the reddening; second, the relative distribution of dust and stars must be known, to infer, by means of a radiative transfer model, the relation between the reddening and the optical depth (or the dust column density). These two steps are obviously coupled together (See for example Xilouris et al. 1997, 1998).

We can easily obtain a lower limit to the optical depth of the ring. We assume the thickness of the dust structure to be negligible so that dust acts like an internal screen for light emitted by a spheroidal bulge. On the near part of the galaxy we assume that all the light is extinguished (i.e. the bulge is all behind the screen). On the far side the situation is reversed, with the bulge un-extinguished. These assumptions are justified by the high inclination of NGC7331 and by the luminous bulge, that has an effective radius similar to the ring (31 arcsec; Boroson 1981). Within this model, B-K on the far side can be regarded as the intrinsic colour of the bulge, and the difference between the two half as the colour excess due to dust extinction. From the difference in B-K of 0.5 mag we can thus derive a optical depth in the V-band of $\approx 0.4$, if a galactic extinction law is assumed. In reality the dust distribution would have a finite thickness; besides scattering and clumpiness should be considered. Inclusion of these features would go in the direction of reducing the extinction for a given quantity of dust (Boissé & Thoraval 1999; Witt & Gordon 1999).

Submm images permit us to derive the V-band optical depth of the dust distribution in a way independent of ge-

---

**Figure 2.** Elliptically averaged surface brightness profiles for 850-µm and 450-µm. Isophote geometrical parameters are described in the text. Error bars represent the standard deviation of the mean inside each elliptical annulus.

**Figure 3.** Correlation between pixels in a B-K smoothed image and 850-µm image, inside a 100 arcsec x 50 arcsec region centred on the galaxy. Filled circles refer to the far side of the galaxy (i.e. east side) and open circles to the near side (i.e. west side). The ring structure evident in 850-µm image (Fig. 1) correspond to fluxes bigger than 60 mJy beam$^{-1}$. Each data point has a random error of $\approx 0.05$ mag.
ometry. The optical depth $\tau_V$ can be related to the flux at $\lambda = 850$-\,$\mu$m using the formula (Hildebrand 1983)

$$\tau_V = \frac{1}{2} \left( \frac{Q_{UV}}{Q_{\lambda_0}} \right) \left( \frac{\lambda}{\lambda_0} \right)^\beta \frac{I_\lambda}{B_\lambda(T)}$$

where $T$ is the temperature of the dust, $I_\lambda$ is the intensity (i.e. the flux per beam divided by the integrated beam size), $B_\lambda(T)$ is the Planck function and $\beta$ the emissivity index. $Q_{UV}$ is the extinction efficiency in the ultraviolet range (1500-3000Å), while $Q_{\lambda_0}$ is the emission efficiency at a reference wavelength $\lambda_0$. The ratio $Q_{UV}/Q_{\lambda_0}$ is quite uncertain: but from Hildebrand (1983) and from Casey (1991) we have derived a mean value $Q_{UV}/Q_{\lambda_0} \approx 1200$ at $\lambda_0 = 125$\,$\mu$m for $\beta = 2$. The value of $Q_{UV}/Q_{\lambda_0}$ for $\beta = 1.5$ has been roughly derived from data in Casey (1991): we use $Q_{UV}/Q_{\lambda_0} = 2100$ at $\lambda_0 = 125$\,$\mu$m. Typically, values of $Q_{UV}/Q_{\lambda_0}$ have uncertainties of a factor of 2-3. The factor 1/2 comes from assuming $\tau_{VUV}/\tau_V = 2$ (Casey 1991). For the ring (mean flux of 70 Jy beam$^{-1}$) we obtain face-on optical depths of $\tau_V = 2.4$ and 9.3, for $\beta = 1.5$ and 2, respectively. At the 1σ isophote $\tau_V = 0.4$ and 0.9. Uncertainties in $\tau_V$ are quite large, because of both the uncertainties in $T$ and in the value $Q_{UV}/Q_{\lambda_0}$. Using temperatures derived with the help of KAO data, optical depths are $\tau_V = 2.6$ and 5.4, for $\beta = 1.5$ and 2, respectively. Telesco et al. (1982) derived a $\tau_V \approx 3$ for the reddest part of the galaxy.

The mass column density of dust can be derived from the optical depth. Adopting a mean dust grain radius of 0.1-\,$\mu$m, a density of 3 g cm$^{-3}$ and an extinction efficiency in the V-band of 1.5 (Hildebrand 1983; Casey 1991), we have obtained ring column densities $N_d = 0.3$ M$_\odot$ pc$^{-2}$ and $N_d = 1.1$ M$_\odot$ pc$^{-2}$ for $\beta = 1.5$ and 2, respectively (see $N_d = 0.04$ M$_\odot$ pc$^{-2}$ and $N_d = 0.1$ M$_\odot$ pc$^{-2}$ at 1σ level). From CO maps of the east and west side of the ring, Tosaki & Shioya (1997) have deduced a mean mass column density for the molecular gas of 150 M$_\odot$ pc$^{-2}$ (we note here that there are possible uncertainties related to the smaller beam size of their observations). An atomic gas column density of 20 M$_\odot$ pc$^{-2}$ has been derived from Bosch (1981) for the position of the ring. The total gas column density for the ring is thus $N_g = 170$ M$_\odot$ pc$^{-2}$. The gas-to-dust mass ratio is then 150 for $\beta = 2$ (570 for $\beta = 1.5$). The value derived for $\beta = 2$ is much closer to the galactic value than IRAS based ratios (Devereux & Young 1996), and in agreement with ISO based determination (Alton et al. 1998a; Davies et al. 1998), as well as with optical-NIR radiative transfer models (Xilouris et al. 1997, 1998).

The dust mass inside 150 arcsec is $M_d = 4 \times 10^7$ M$_\odot$ for $\beta = 2$ (3.5 M$_\odot$ for $\beta = 1.5$). From Alton et al. (1998a) data, covering a larger area ($\approx 10$ arcmin), we can derive a dust mass of $M_d = 1.2 \times 10^8$ M$_\odot$ (for both values of $\beta$). Therefore the total mass is at least three times larger than the one we have derived here. This shows that there is a large and diffuse component of dust ($> 70$ per cent in mass) that is not associated with the molecular ring. It is interesting to note that an extended dust distribution may be the reason why some millimetre and submm observations (Alton et al. 1998a; Davies et al. 1998) have failed to detect cold dust, because of the small size of the bolometers used compared to the extent of the dust (Clements et al. 1993).

Acknowledgements. We are grateful to Iain Coulson at JCMT for his help and support during observations and data reduction. It is also a pleasure to thank Beverly Smith for providing us with KAO data, Manolis Xilouris for the B-band image and Harley Thronson for help with the K-band data.

REFERENCES

Alton P. B., Trewella M., Davies J. I., Evans R., Bianchi S., Gear W., Valenti J., Witt A., 1998, A&A, submitted.

Alton P. B., Bianchi S., Rand, R. J., Xilouris, E. M., Davies J, Trewella M., 1998b, ApJ, submitted.

Block D. L., Witt A. N., Grosbol P., Stockton A., Moneti A., 1994, A&A, 288, 383

Boissé P., Thoraval S., 1996, in Block D. L., Greenberg J. M., eds, New Extragalactic Perspectives in the New South Africa. Kluwer, Dordrecht, p. 187

Boroson T., 1981, ApJS, 46, 82

Bosma A., 1981, AJ, 86, 1791

Casey S. C., 1991, ApJ, 371, 183

Clements D. L., Andreani P., Chase T. S., 1993, MNRAS, 261, 299

Cowan J. J., Romanishin W., Branch D., 1994, ApJ, 436, L139

Davies J. I., Alton P. B., Trewella M., Evans R., Bianchi S., 1998, MNRAS, accepted

de Vaucouleurs G., de Vaucouleurs A., Corwin H.G., Buta R. J., Paturel G., Fouque P., 1991, Third Reference Catalogue of Bright Galaxies. Springer, New York

Devereux N. A., 1995, in Davies J. I., Burstein D., eds, Proc. NATO ARW, NATO Asi Ser. 409, The Opacity of Spiral Disks. Kluwer, Dordrecht, p. 269

Devereux N. A., Young J. S., 1990, ApJ, 359, 42

Disney M., Davies J., Phillips S., 1989, MNRAS, 239, 939

Eales S. A., Wynn-Williams C. G., Duncan W. D., 1989, ApJ, 339, 859

Garcia-Gomez C., Athanassoula E., 1991, A&A, 89, 159

Hildebrand R. H., 1983, QJRAS, 24, 267

Hughes S. M. G. et al., 1998, AJ, accepted

Jenness T., Lightfoot J. F., 1997, Starlink User Note 216.1

Mas S. et al., 1995, ApJ, 452, 253.

Pogge R. W., 1989, ApJS, 71, 433

Reach W. T. et al., 1995, ApJ, 451, 188

Sandell G., 1997, Starlink Cookbook 11.1

Smith B. J., 1998, ApJ, accepted

Smith B. J., Harvey P. M., 1996, ApJ, 468, 139

Sodroski T. J., et al., 1994, ApJ, 426, 638

Sodroski T. J., Odegard N., Arendt R. G., Dwek E., Weiland J. L., Hauser M. G., Kelsall T., 1997, ApJ, 480, 173

Telesco C. M., Gatley I., Steward J. M. G., Dwek E., Weiland J. L., Hauser M. G., Kelsall T., 1997, ApJ, 480, 173

Tosaki T., Shioya Y., 1997, ApJ, 484, 664

Trewella M., 1997, PhD Thesis, University of Wales Cardiff

von Linden S., Reuter H.-P., Heidt J., Wielebinski R., Pohl M., 1996, A&A, 315, 52

Whittet D. C. B., 1992, Dust in the Galactic Environment. IOP, Bristol

Witt A. N., Gordon K. D., 1996, ApJ, 463, 681

Xilouris E. M., Kylafis N. D., Papamastorakis J., Paleologou E. V., Haerendel G., 1997, A&A, 325, 135

Xilouris E. M., Alton P. B., Davies J. I., Kylafis N. D., Papamastorakis J., Trewella M., 1998, AA, 331, 894

Young J. S., Scoville N., 1982, ApJ, 260, L41