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ISO observations of hot dust in the nucleus of the S0 galaxy NGC 3998*

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Abstract. ISOCAM maps of the Seyfert 1 S0 galaxy NGC 3998 between 4.5μm and 15μm detect both extended emission from the bulge stars and strong point source emission from the nucleus. The inner regions of NGC 3998 appear to contain a few thousand solar masses of warm ($\sim$ 200 K) dust, probably associated with the AGN.

Key words: galaxies: elliptical and lenticular, cD – galaxies: individual: NGC 3998 – galaxies: ISM – galaxies: Seyfert

1. Introduction

This *Letter* describes measurements by the Infrared Space Observatory (ISO) of the distribution of mid-infrared (4 – 15μm) emission in NGC 3998. These are the first results from an ISO program to image a sample of early-type galaxies with a wide range of properties (optical colors and morphology, H I content, etc.) between 4μm and 200μm, to study the distribution of interstellar dust and of the cool evolved stellar populations in these systems.

NGC 3998 is an S0 galaxy of diameter D_{25} = 2.′7 × 2.′2, with a bulge-to-disk ratio of 0.4 (Fisher et al. 1996). Like several other early-type galaxies in our sample, it contains extended H I, in this case in a polar ring of diameter $\sim$ 2.5 arcminutes (Knapp et al. 1985). In addition to the bulge and disk, numerous optical images (cf. the HST FOC image described by Fabbiano et al. 1994) show a very bright semi-stellar nucleus. Further evidence of an active galactic nucleus is the Seyfert-like emission-line spectrum (Filippenko and Sargent 1985; Giurcin et al. 1991), point-source X-ray emission (Brinkmann et al. 1995), and a non-thermal nuclear radio point source of strength $\sim$ 100 mJy at centimeter wavelengths (Wrobel and Heeschen 1991). Perhaps the most striking property of the nuclear region is the stellar velocity dispersion; $\sigma_\star \geq$ 300km s^{-1}. This dispersion is anomalously large for a galaxy of this luminosity, is larger than the circular velocity measured by H I (Knapp et al. 1985), and increases as smaller apertures are used (Nelson and Whittle 1995; Fisher et al. 1996).

NGC 3998 is weakly detected in all four IRAS bands, with colors typical of those found in galaxies with active nuclei (Condon et al. 1995). The emission at 60μm and 100μm most likely arises from diffuse interstellar dust. Most bright early-type galaxies are weakly detected at 12μm, probably due to the photospheres and circumstellar shells of the cool, evolved stellar population. However, NGC 3998 is unusual. Much of its 12μm emission appears to be concentrated to the inner galaxy (Knapp et al. 1992); the 12μm emission is much brighter relative to the starlight than in typical early-type galaxies; (the global ratio of flux densities at 12μm and 2.2μm, $S_{12}/S_{2.2}$, is 0.3 for NGC 3998, compared with the values of $\sim$ 0.1 found for other such galaxies – Knapp et al. 1992); and small-aperture measurements near 12μm at both UKIRT and IRTF (Willner et al. 1985; Sparks et al. 1986; Knapp et al. 1992) show that much ($\geq$ 40%) of the 12μm flux density arises within a few arcseconds of the nucleus.

Our ISO program includes observations of this galaxy at wavelengths between 4μm and 200μm. Here we present the first results, maps of the 4 – 15μm emission made with ISOCAM.

2. Observations and results

NGC 3998 was observed by ISO on 8 April 1996. The galaxy was imaged by ISOCAM using the three broad-band filters LW1 (centered at 4.5μm), LW2 (6.75μm), and LW3 (15μm), employing a 3 × 3 raster (CAM01) to improve the flat fielding. In each case we used the 6″-per-pixel observing mode with 12″ offsets between adjacent raster lines/rows, giving an unvignetted

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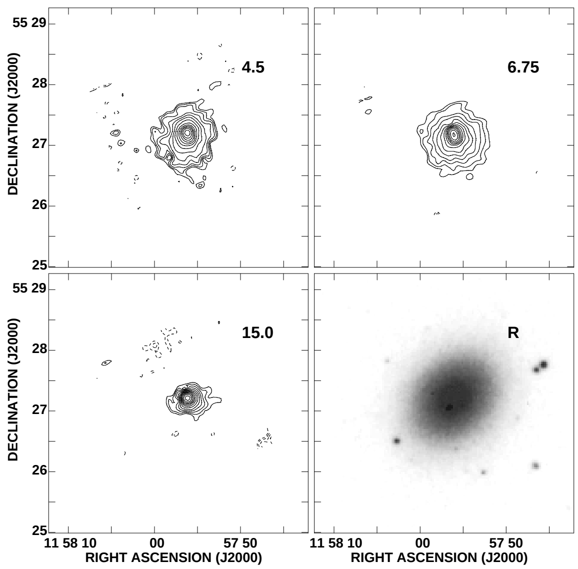

Fig. 1. Contours: ISOCAM 4.5, 6.75, 15μm; grayscale: digitized POSS red plate. Contour levels are $\pm 2^{n/2}$C, n = 2, 3, . . ., with C = (0.2, 0.2, 0.5) mJy per 6 arcsec pixel for the (4.5, 6.75, 15)μm maps. The peaks in the images are (33, 27, 57) mJy per 6 arcsec pixel, while the total flux densities are $\sim$(200, 220, 240) mJy, at (4.5, 6.75, 15)μm. The absolute fluxes are very uncertain. The total ISOCAM field-of-view is 3×3 arcminutes; this together with the planar background removal (see text) would suppress any smooth emission on scales larger than a few arcminutes. All CAM images were processed by subtraction of a planar background from the outer regions (excluding bad columns/rows), then interpolating from spacecraft orientation and 6 arcsec pixels to J2000 coordinates and the 1.7 arcsec pixels of the digitized POSS plate. The CAM maps have also been shifted 10.″2 east (see text).

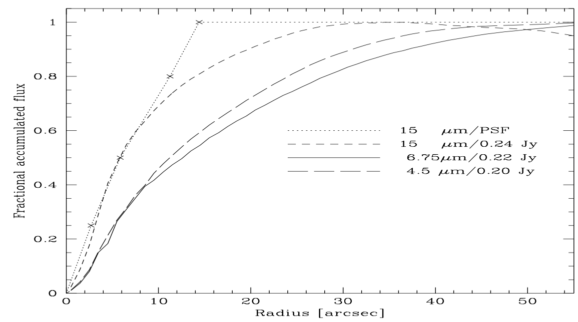

Fig. 2. Fraction of total flux density enclosed within a range of circular apertures, assuming total flux densities of (200, 220, 240) mJy at (4.5, 6.75, 15)μm. The circles were centered on the peaks of the emission, as determined by inverse-parabolic fits to the maxima. The expected point-spread function at 15μm from the pre-launch *ISOCAM Observer's Manual* (Fig. 2) is shown for comparison; the 4.5 and 6.75μm point-spread functions should correspond to delta functions in the 6 arcsecond pixels used. At least 80% of the 15μm flux density comes from a region of order or less than a few arcseconds across. By contrast the 4.5 and 6.75μm emission is clearly extended.

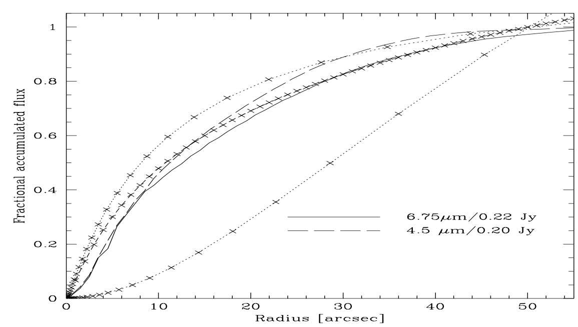

Fig. 3. Fraction of total flux densities at 4.5 and 6.75μm enclosed within a range of circular apertures, as in Fig. 2. The X'd lines show the distribution expected for the bulge (upper line), disk (lower line), and total (many Xs, middle line) stellar light distribution, as given by the bulge/disk decomposition of Fisher et al. (1996). All stellar curves have been normalized to unity at 50 arcseconds, to account for the CAM background subtraction. The short-wavelength CAM emission is too centrally concentrated to reside in the disk; it must be associated primarily with the bulge.

field of $3' \times 3'$. Since the expected diffraction-limited resolutions at these wavelengths are 1.″5, 2.″2, and 5″ respectively, the images are badly undersampled. The data were flat-fielded, dark-subtracted, aligned, and calibrated at ESTEC via the Auto-Analysis pipeline (Siebenmorgen et al. 1996). Images at all three wavelengths have considerable background, due mostly to zodiacal light. This was removed by fitting a plane to the blank areas of the image, excluding the noisy edge pixels; note that this procedure would remove any real emission which extends over more than a few arcminutes. The image was then regridded onto 1.″7 pixels, and rotated from spacecraft to J2000 orientation.

Although nominally centered on the accurate VLA position measured by Wrobel and Heeschen (1991), the CAM images at all three wavelengths show emission displaced from the optical galaxy. We assume that this offset is instrumental, and have shifted the maps 10.2″ to the east to align the ISO and the optical emission.

Figure 1 shows a montage of the ISOCAM images, with the digitized Palomar red image for comparison. The emission is clearly extended at 4.5μm and 6.75μm, while the 15μm emission is basically unresolved. The isophotes of the extended emission are round, showing no elongation along the galaxy's major axis. Summing the emission over circular apertures centered on the peaks gives the cumulative flux distributions shown in Fig. 2. The 15μm diffraction limited beam (taken from data given in the pre-launch *ISOCAM Observer's Manual*) is shown for comparison; almost all of the 15μm flux comes from a central point source, while the shorter wavelength emission is mostly from the extended galaxy, i.e. is likely to be associated with the starlight. Figure 3 compares the 4.5μm and 6.75μm flux with that of the blue light, as calculated from the bulge/disk decomposition of Fisher et al. (1996). Both these radial distributions and the relative roundness of the ISOCAM and optical bulge emission compared to the disk (Fisher et al. 1996) suggest that most of the infrared flux at 4.5μm and 6.75μm arises from the bulge.

Table 1. Flux Densities for NGC 3998

Filter	λ_0 (μm)	S_ν(tot) (mJy)	S_ν(nuc)/S_ν(tot)
CAM-LW1 [1]	4.5		0.3
CAM-LW2 [1]	6.75		0.4
CAM-LW3 [1]	15.0		0.8
m_{2000} [2]	0.20	2.16 ± 1.0	
U_T^0 [3]	0.37	28.2 ± 3.3	
B_T^0 [3]	0.44	108 ± 12	
V_T^0 [3]	0.55	219 ± 25	
K [4]	2.2	460	
N [5]	10.1	53.1 ± 4.2	
IRAS [7]	12	130 ± 23	
IRAS [7]	25	120 ± 21	
IRAS [7]	60	570 ± 27	
IRAS [7]	100	1020 ± 110	

[1] this paper; flux scale highly uncertain
[2] Donas et al. 1987 (balloon data)
[3] RC3 (de Vaucouleurs et al. 1991)
[4] Knapp et al. 1992 estimate of total K-band flux density
[5] weighted average of small (6 – 8″) aperture measurements of Willner et al. 1985, Sparks et al. 1986, and Knapp et al. 1992
[6] Willner et al. 1985; 8″ aperture
[7] Knapp et al. 1989, from co-adds

3. Discussion

The results are summarized in Table 1, which gives the filter name, the mean wavelength and the approximate fraction of the total emission at each wavelength which is within the central pixel of the array; this is a rough measure of the fraction of the emission which arises from the nucleus. As Table 1 shows, this fraction rises with increasing wavelength, and its values are in agreement with the measurements of Knapp et al. (1992).

The reductions of the ISOCAM data used in this paper were made with a preliminary version of the Auto-Analysis software (Siebenmorgen et al. 1996) which did not produce final, reliable flux densities; however, these reductions are all that are available to us at the present time. Accordingly, we do not use the flux densities themselves in the analysis, and Table 1 also lists optical and infrared flux densities from the literature. We have not included the low signal-to-noise Q band measurement by Willner et al. (1995). The mean N-band small aperture flux density, the IRAS 12μm and 25μm flux densities and the ISOCAM maps all show that much of the flux between 5 and 20μm arises in the nuclear regions of NGC 3998 and that the fraction of the total flux contained in this region rises towards longer wavelengths. The nuclear infrared emission thus has a lower color temperature than does the starlight and is not a dense concentration of stars in the inner regions of the galaxy.

The small-aperture 10.1μm flux density and the 25μm flux density measured by IRAS (assuming that it is entirely from the central regions, as seems likely from the trends shown by the ISOCAM data) give a rough color temperature of 250 K, suggesting that the source of the emission is warm interstellar dust. The corresponding temperature for dust whose emissivity depends on wavelength as $Q_\lambda \propto \lambda^{-1}$ is about 200 K. The dust temperature obtained from the 60μm and 100μm flux densities is about 40 K, and the dust emission from this galaxy thus appears to have at least two components: a hot component in the nucleus and a colder component which is likely to be more diffuse and extended. The hot dust must be in the very inner regions of the galaxy, whether it is heated by starlight (which only has the necessary density within about a hundred parsecs of the center) or, more likely, at least partially by the active nucleus, for example by Lyα absorption. At a distance of 17.6 Mpc (H_0 = 75 km $s^{-1}Mpc^{-1}$) (Fisher et al. 1996) the corresponding hot dust mass is very roughly 4×10^3 $M_\odot$, which suggests about $7 \times 10^5 M_\odot$ of gas. In any case this warm dust mass is far below the $7 \times 10^5 M_\odot$ derived from a similar single-temperature fit to the 60μm and 100μm data, while the amount of associated gas is much smaller than the $4 \times 10^8 M_\odot$ of H I observed by Knapp et al. (1985).

Many other early-type galaxies have dust in their inner kpc or so (Welch et al. 1991; van Dokkum and Franx 1995; Knapp et al. 1996), but very few have a compact, hot dust cloud in the center like that in NGC 3998. The only other galaxy in the sample of Knapp et al. (1992) to have this property is NGC 1052; for example, NGC 4278, whose properties are very similar to those of NGC 3998 and NGC 1052, does not. Statistical analyses of large samples of early-type galaxies show that those with cold interstellar gas detected by its CO and/or H I emission are much more likely to contain dust which is detected by IRAS, and vice versa (e.g. Walsh et al. 1990; Knapp and Rupen 1996). However, the detailed relationship between dust in the inner regions and the extended gas structures remains unclear. Even IRAS was most sensitive to relatively warm dust, and there may be yet colder grains lurking in the outskirts of this and other early-type galaxies. Our ISOPHOT images of the 20 – 200μm emission from NGC 3998 and many other early-type galaxies should settle this question, and we look forward to their analysis.

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