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INTERFEROMETRIC OBSERVATIONS OF 1.4 MILLIMETER CONTINUUM SOURCES

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ABSTRACT

We present 1.4 mm continuum measurements for a sample of 15 Galactic and extragalactic sources acquired with the Owens Valley Millimeter-Wave Interferometer. Maps at 3″ resolution reveal compact dust emission regions in L1551 IRS 5, HH 7–11, NGC 7538 IRS 1, and DR 21(OH), as well as in Arp 220 where approximately 50% of the total 1.4 mm flux originates from a compact source, less than 650 pc in radius, centered on the near-infrared nucleus. The mass of interstellar matter in the central source of Arp 220 is approximately 3×10^9 $M_\odot$. Comparison of the 1.4 and 2.7 mm dust emission in 10 Galactic sources (with no significant free-free emission) indicates a spectral index of 3.0 ± 0.2 for the frequency dependence of the observed small-scale flux. Assuming the emission is optically thin, the grain emissivity is $\epsilon_\nu \propto \nu^{1.0 \pm 0.2}$, suggesting that two-dimensional layered materials such as amorphous carbon or layer-lattice silicates are important contributors to the long-wavelength emissivity.

Subject headings: interferometry — interstellar: grains — stars: formation

I. INTRODUCTION

The millimeter-wave continuum radiation from interstellar dust is a potentially excellent probe of the mass distribution in heavily obscured, star-forming regions. Even in the most opaque regions ($A_V \geq 100$ mag), the dust emission will be optically thin at $\lambda = 1$ mm. Moreover, the dust emission is only linearly dependent on the grain temperature, which can in most cases be readily deduced to within 20% from shorter wavelength infrared data. In this *Letter*, we report the first interferometric observations in the 1.4 mm wavelength region. Maps of the dust emission in a 350 MHz continuum channel at 3″–5″ resolution are presented for the ultraluminous infrared galaxy Arp 220, the Galactic star-forming regions DR 21(OH) and NGC 7538 IRS 1, and the circumstellar nebulae in L1551 IRS 5 and HH 7–11. We also describe a quick-look survey of 12 other sources which was carried out in order to determine the long-wavelength dust emissivity law. $C^{18}O$ spectral line aperture synthesis mapping of DR 21(OH) and L1551 IRS 5 is reported in an accompanying *Letter* (Padin *et al.* 1989).

II. OBSERVATIONS

Continuum observations at 1.4 mm (219.5 GHz) were acquired with the Owens Valley Radio Observatory (OVRO) Millimeter-Wave Interferometer during 1988 March. The three 10.4 m dishes were equipped with SIS receivers with double-sideband receiver temperatures of 100–200 K. This was the first astronomical use of the new dual channel (1.4 mm/2.6 mm) receiver systems (Woody 1988) in the 1.4 mm band. The instrumental phase stability was excellent, due to the implementation of a new local oscillator phase-lock system (Padin, Woody, and Scott 1988). Intrinsic phase variations were less than 5° on time scales of minutes and about 10° on time scales of hours and typical atmospheric phase drifts of 40°–60° in an hour were removed with observations of point source calibrators every 20–30 minutes. The synthesized beams, which varied somewhat from source to source, were ~3″.3 (FWHM) in the best cases. The telescope primary beam is approximately 34″ at $\lambda = 1.4$ mm; the largest size scale adequately sampled by the observations is ~20″.

Mars was the primary flux standard (assumed $T_B = 207$ K) and 3C 273 (25 Jy) and 3C 84 (12.5 Jy) were established as secondary calibrators. The uncertainty in the absolute flux determinations is estimated to be 30%, mainly due to changes in atmospheric coherence on the time scale of hours, and to uncertainties in the telescope pointing, which could be up to ~15″ near sunrise. The rms noise in the most sensitive continuum map (Arp 220) was ~20 mJy per beam. Quick-look continuum observations of additional sources were made while the array was in the tightest configuration, with 15, 30, and 45 m east-west baselines. Typical uncertainties in the absolute flux measurements for these survey objects are also 30%.

III. RESULTS

Figure 1 shows contour maps of the 1.4 mm continuum emission for four galactic sources: HH 7–11, L1551 IRS 5, DR 21(OH), and NGC 7538 IRS 1. Three of these, HH 7–11, L1551 IRS 5, and NGC 7538 IRS 1, are unresolved. DR 21(OH) is clearly resolved into a double source with a possible additional component extended to the northwest. Figure 2 shows the position of the 1.4 mm continuum source in Arp 220 superposed on a contour map of a Gunn *r*-band image (Sanders *et al.* 1989). The total flux densities and peak positions for the mapped sources are given in Table 1. In this table, the 1.4 mm fluxes on a projected 15 m baseline, and the pointing centers of the survey source observations, are also presented. Comparison of our flux measurement for Arp 220, 0.14 Jy, with the heterodyne observations in a 33″ beam which yield a flux of 0.34 ± 0.08 Jy (Thronson *et al.* 1986) or the more recent bolometer measurement of 0.25 Jy in an 11″ beam (R. Zylka, private communication) indicates that approximately half of the total emission is concentrated in the central 3″.5.

IV. DISCUSSION

a) Dust Emissivity Law

Table 1 contains not only 1.4 mm but also 2.7 mm continuum flux measurements obtained at similar spatial resolution.

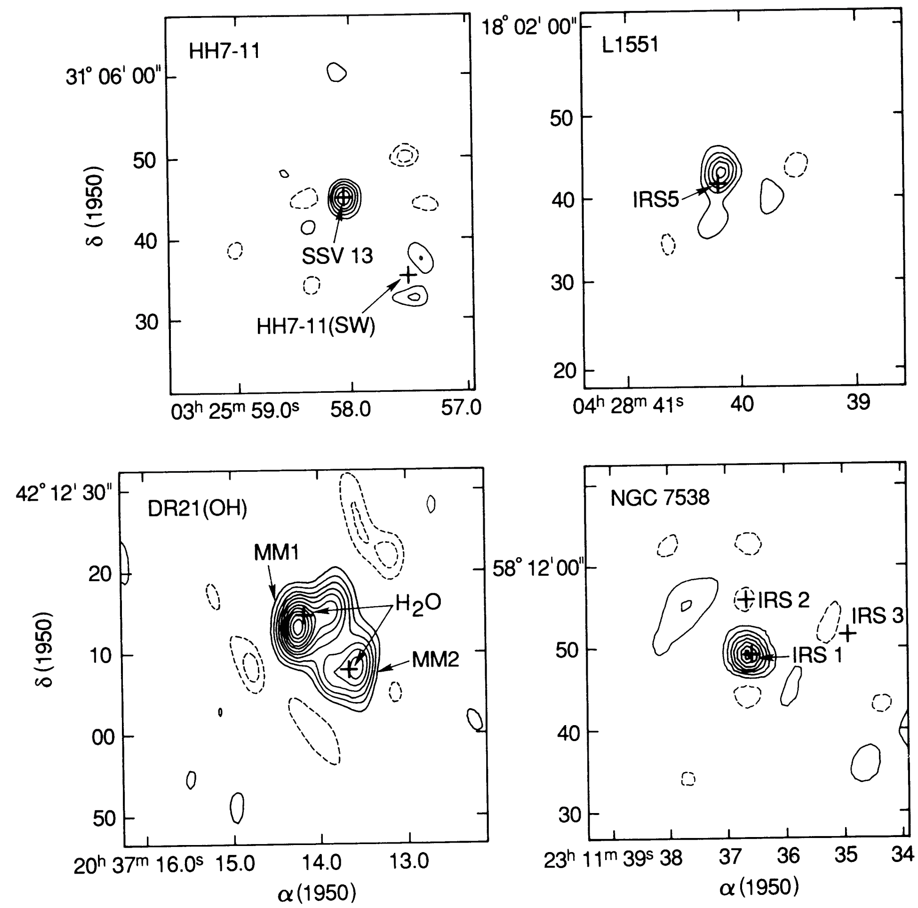

FIG. 1.—Contour maps of the 1.4 mm continuum emission are shown for HH 7–11, L1551 IRS 5, DR 21(OH), and NGC 7538 IRS 1. The synthesized beam for HH 7–11, L1551 IRS 1, and NGC 7538 IRS 1 was approximately 3".3 FWHM; for DR 21(OH), the beam was 6".8 by 3".4 at position angle 6°. The contour levels start at 2 σ and are spaced by 1 σ and the highest contour levels are 0.36, 0.68, 1.80, and 1.15 Jy per beam respectively.

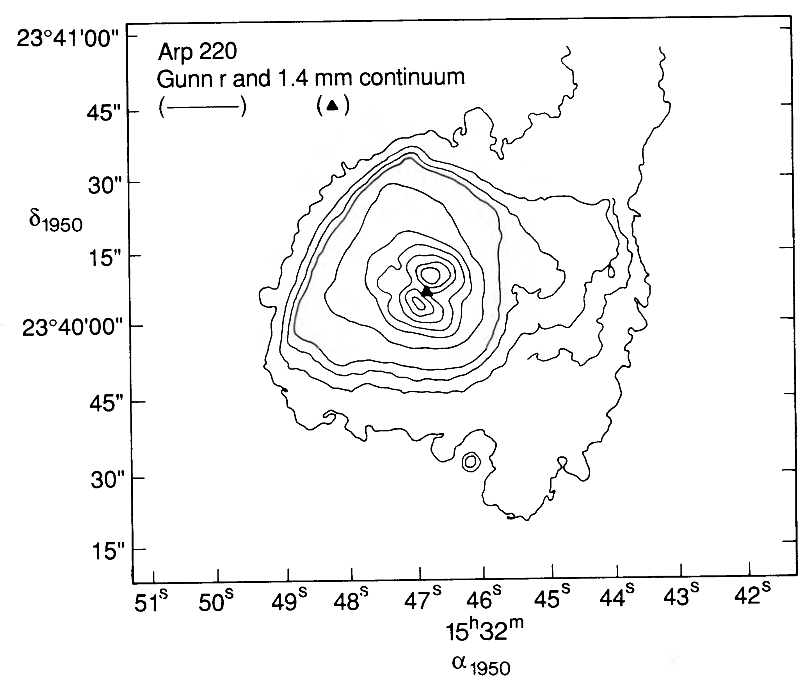

FIG. 2.—Contour map of the Gunn *r*-band optical image for Arp 220 obtained by Sanders *et al.* (1989) on the Palomar 5 m telescope is shown with the position of the unresolved 1.4 mm continuum source superposed (*triangle*). Note that the continuum source is centered on the region of obscuration, between the two *r*-band peaks.

TABLE 1

1.4 MILLIMETER CONTINUUM MEASUREMENTS

Source	R.A.(1950)	Decl.(1950)	1.4 mm Flux[a] (Jy)	2.7 mm Flux[b] (Jy)	Comments[c]
		Mapped Sources			
HH 7–11	03:25:58.2	31:05:47	0.4 ± 0.05	0.08	Dust
L1551 IRS 5	04:28:40.2	18:01:42	0.7 ± 0.1	0.17	Dust
NGC 3690	11:25:42.6	58:50:14	≤0.12	...	Dust
Arp 220	15:32:46.9	23:40:07	0.14 ± 0.02	...	Dust
DR 21(OH) MM 1	20:37:14.2	42:12:13	3.2 ± 0.2[d]	0.48	Dust
DR 21(OH) MM 2	20:37:13.6	42:12:08			Dust
NGC 7538 IRS 1	23:11:36.7	61:11:49	2.0 ± 0.3	2.6	H II
		Quick Look Sources			
W3(OH)	02:23:16.5	61:38:57	4.5 ± 0.4	3.8	H II
GL 490	03:23:39.2	58:36:36	2.1 ± 0.2	0.28	Dust
DG Tau	04:24:01.0	25:59:35	0.7 ± 0.2	0.08	Dust
LkHα 101	04:26:57.2	35:09:55	0.7 ± 0.2	...	H II wind
HL Tau	04:28:44.4	18:07:36	1.0 ± 0.2	0.12	Dust
Orion CS3	05:32:46.1	−05:26:02	4.5 ± 0.5	0.30	Dust
Ori/IRc2	05:32:46.9	−05:24:26	20.0	1.0	Dust + H II
Orion CS1	05:32:47.8	−05:24:00	3.5 ± 0.7	0.36	Dust
NGC 2024	05:39:12.7	−01:57:06	1.5 ± 0.2	0.20	Dust
NGC 2071	05:44:30.0	00:20:40	1.9 ± 0.3	0.13	H II + Dust
NGC 2264	06:38:24.9	09:32:29	1.1 ± 0.4	0.11	H II + Dust
IRC +10216	09:45:14.8	13:30:40	0.5 ± 0.1	...	Stellar wind
S106	20:25:23.8	37:12:48	1.8 ± 0.3	...	H II wind
CRL 2688	21:00:20.0	36:29:44	1.6 ± 0.3	...	H II + dust
Cep A	22:54:19.2	61:45:44	4.2 ± 0.4	0.30	H II

[a] Estimated from 15 m baseline, or map. Errors denote statistical uncertainty only.
[b] Flux densities from maps made with OVRO Array.
[c] Identification as H II emission determined from centimeter radio flux.
[d] Total flux of MM 1 and MM 2.

In most instances the 1.4 mm flux is more than a factor of 4 greater than at 2.7 mm, suggesting that thermal emission from dust is more important than free-free emission from ionized gas for those sources. In many cases, the absence, or low level, of the centimeter wavelength radio emission implies that essentially *all* of the millimeter flux arises from dust. For these objects (see Table 1), comparison of the 1.4 and 2.7 mm flux densities indicates an average ratio of 7.8 ± 1.1, corresponding to a spectral index ($\lambda^{-\alpha}$) of $\alpha = 3.0 \pm 0.2$ for the wavelength dependence of the observed flux. In the remaining sources, the emission is probably a combination of dust and free-free, the former dominating at 1.4 mm and the latter at 2.7 mm.

Determination of the wavelength dependence of the dust emissivity, ϵ_ν, from this spectral index measurement is predicted on the assumption that the emission is optically thin at both wavelengths and that the dust is sufficiently warm for the Rayleigh-Jeans approximation to hold ($h\nu \gg kT_D$). The resulting spectral dependence for the dust emissivity is $\epsilon \propto \nu^{1.0\pm0.2}$. A similar spectral index was derived by Campbell *et al.* (1976) for the dust in the carbon star IRC +10216. For an unresolved source, the optically thin assumption requires that the true source angular size exceeds the product of the beam size and the observed apparent brightness temperature, divided by the true source brightness temperature. Adopting a characteristic source temperature of 50 K, and an observed apparent brightness temperature of 2 K, corresponding to a 1 Jy emission source, we find that the source size must be greater than 0$''$.7 in order to assure optical thinness at 1.4 mm.

An extensive discussion of the expected long-wavelength dust emissivity is presented by Tielens and Allamandola (1987). In general, it has been expected that both crystalline and amorphous materials have the same ν^2 wavelength dependence for the far-infrared absorption and emissivity. An exception to the quadratic dependence is found for layered materials in which the phonons are limited to two dimensions. Both amorphous carbon and layered silicates have such two-dimensional structure and show far-infrared absorption with wavelength dependences between ν^1 and $\nu^{1.5}$ (Koike, Hasegawa, and Manabe 1980; Day 1976). The derived emissivity therefore provides strong support for planar grains dominating the far-infrared dust emission.

b) Mass Determination

For the Galactic sources, high-resolution 1.4 mm interferometry provides an excellent probe of the dense dust cocoons associated with individual young stars. Having determined a reliable emissivity law using measurements with comparable spatial resolution at two long wavelengths, accurate estimates can be obtained for the nebular masses based on the dust emission. Assuming it is optically thin, the 1.4 mm flux is a probe of the total mass of material in the immediate circumstellar environment. Using the relation between the 250 μm flux and the gas and dust mass derived by Hildebrand (1983), and extrapolating to 1.4 mm assuming emissivity varies as ν^β, we obtain

$$M = 1.91 \times 10^{-2} \left(\frac{\lambda_{\rm mm}}{0.25}\right)^{\beta+3} S_{\rm Jy}\left(e^{14.4/\lambda_{\rm mm} T_D} - 1\right) d_{\rm kpc}^{\,2}\, M_\odot\,, \tag{1}$$

where T_D is the dust temperature, S_{Jy} is the flux density in Jy at wavelength λ_{mm}, and d_{kpc} is the distance in kpc. Adopting a typical temperature of 50 K and $\beta = 1.0$, the derived masses for the galactic sources L1551 IRS 5 (160 pc), HH 7–11 (350 pc), and DR 21(OH) (3.0 kpc) are 0.08, 0.2, and 125 $M_{\odot}$, respectively; H II contamination prevented the determination of a mass for NGC 7538 IRS 1. There is a factor of 2 uncertainty in the derived masses due to the range (0.8–1.2) in the derived emissivity index. As long as the dust temperature exceeds 10 K, the masses scale inversely with the assumed temperature. For the unresolved source in Arp 220 (77 Mpc), the mass is 3×10^9 $M_{\odot}$. The uncertainty in these estimates is largely due to the factor of 2 uncertainty in the relation between 250 μm flux and gas and dust mass.

Particularly noteworthy is the central concentration of the observed flux (and by inference the mass) distributions in the Galactic sources, indicating that in each case a very centrally condensed nebula exists long after the initial protostellar collapse, as might be anticipated from their near-infrared continuum emission. Our detections of nebulae of a few solar masses within a few kpc with the interferometer, underscores the potential of this technique for detailed studies of nearby star formation.

c) Arp 220

The very great central concentration of material implied by the 1.4 mm observations of Arp 220 confirms and amplifies the earlier OVRO CO(1–0) interferometric measurement which indicated that approximately 70% of the total CO emission was contained in a nuclear source less than 5″ in size (Scoville *et al.* 1986). From the new observations, it is clear that the gas and dust is confined to an area of radius less than 650 pc, less than half the previous upper limit and similar to the bright 10 μm emission region (Becklin and Wynn-Williams 1987). The mean volume density in the region is 50–100 H_2 cm^{-3} (if the matter is uniformly distributed over a spherical volume), very like that found *within* giant molecular clouds in the Galaxy. The 1.4 mm interferometer peak is within 1″ of the radio and near-infrared peak (Condon and Dressel 1978; Neugebauer *et al.* 1987) and, as can be seen in Figure 1, coincides with the peak optical absorption in the *r*-band image.

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