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A millimetre search for dust in the globular clusters M 3 and M 22

A.J. Penny[1], **A. Evans**[2], **and M. Odenkirchen**[3]

[1] Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, U.K.
[2] Department of Physics, Keele University, Keele, Staffordshire, ST5 5BG, U.K.
[3] Sternwarte der Universität Bonn, Auf dem Hügel 71, D-5300 Bonn 1, Germany

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Abstract. We have conducted the first millimetre wavelength search for interstellar dust within globular clusters, by carrying out observations of M 3 and M 22. We have found no dust in the central 14″ and 18″ of the clusters, respectively, to a limit of $\sim 10^{-3} \ldots 10^{-1}\,M_\odot$ (M 3) and $\sim 10^{-5} \ldots 10^{-3}\,M_\odot$ (M 22), depending on the absorption efficiency assumed for the dust. If, as we argue, the appropriate absorption efficiency is for *circumstellar* rather than *interstellar* dust, the smaller upper limits are appropriate. These limits are comparable with, or somewhat tighter than, those obtained in previous searches at other wavelengths, although tighter upper limits on *mass per unit area* or on *mass per unit beam* are generally provided by IRAS data. However, observations at millimetre wavelengths are sensitive to dust at significantly lower temperatures. These results are consistent with previous searches for dust in clusters, which have given upper limits below $10^{-2} M_\odot$, except for a possible detection in 47 Tuc at the $3\,10^{-4} M_\odot$ level.

M 3 and M 22 are expected to have produced some $0.05\,M_\odot$ and $8\,10^{-4}\,M_\odot$ of dust respectively since their last Galactic plane crossing, as calculated from the rate of injection of dust into the interstellar medium by evolving member stars and from the orbits of the clusters. The discrepancy between observation and theory is discussed.

Key words: dust – globular clusters: general – globular clusters: individual (M 3) – globular clusters: individual (M 22) – Galaxy: kinematics and dynamics – dust; extinction

1. Introduction

A typical globular cluster (GC) last crossed the Galactic plane some $10^7 \ldots 10^8$ years ago. At that time any gas and dust it contained would be removed tidally and by ram pressure. Since then up to a thousand of its stars will have gone through the post-main-sequence (RGB, HB, AGB, post-AGB) evolutionary stages, each star losing about $0.3\,M_\odot$ of matter into the interstellar medium. Thus some $10^2 \ldots 10^3\,M_\odot$ of gas and some $0.1 \ldots 1.0\,M_\odot$ of dust would be expected now to be in the cluster, if no loss from the cluster occurs.

However neither gas nor dust at this level has yet been detected in any cluster, with upper limits some hundred times less than the expected values. It is thus presumed that some mechanism(s), as yet undetermined although there are many candidates, strips the matter out as it is injected.

The alternative explanation, that not as much matter has been lost from the stars as expected, seems very unlikely. For this to happen either not as many stars will have had to evolve through the mass-loss evolutionary stages as expected, or each star will have had to lose less mass than expected, both of which scenarios which would cause major problems for what are thought to be well determined aspects of stellar evolution. For a discussion of this see Roberts (1988).

The sole believable detection of interstellar matter in a GC comes from IRAS pointed observations of 47 Tuc (Gillett et al. 1988), where $3\,10^{-4}\,M_\odot$ of dust was detected. If this is typical, then dust must be stripped out of clusters on a timescale of about $10^4 \ldots 10^5$ years in order to balance the input of dust from evolving stars. With only the one detection – in what is a very massive cluster – it is impossible to say either if that amount of dust is typical, or to discriminate between the different proposed stripping mechanisms.

A determination of, or even stronger limits on, the amount of interstellar matter in GCs would clearly be a major step in determining the mechanism(s) by which GCs are purged of their interstellar matter.

There has been no previous attempt to search for the dust component of this matter at continuum millimetre wavelengths, even though it is a sensitive probe for dust. We have therefore started a programme of millimetre observations of GCs, and present here the results for two clusters, M 3 and M 22.

2. Previous Searches

Searches for intra-cluster matter fall into two groups, those that search for gas, and those that search for associated dust. A com-

Send offprint requests to: A. J. Penny

prehensive list of searches is given by Lynch & Rossano (1990; hereafter LR90) and these are summarized here; a full list of references may be found in LR90.

2.1. Gas

Searches for gas have been conducted in a number of wavelength bands:

(i) X-ray. Einstein observations show possible evidence for intracluster gas interacting with a hot Galactic corona;

(ii) Optical. Hα searches have been negative (e.g. a limit of 0.7 $M_\odot$ for HII by Hesser & Shawl 1977);

(iii) Near-IR. 2…10 μm work has produced upper limits or conflicting results;

(iv) Millimetre. GCs have been surveyed for CO molecular gas by its line emission (see also Smith et al. 1995);

(v) Radio. 21 cm searches have been negative, as have searches for free-free emission in the 2…10 GHz ranges (e.g. a limit of 0.8 $M_\odot$ for neutral hydrogen by Conklin & Kimble 1976).

The best upper limits from these searches have been in the range 0.1…1.0 $M_\odot$ of gas.

2.2. Dust

Searches for dust have also been carried out in a number of wavelength bands; a full list of references may again be found in LR90.

(i) Optical. Searches for 'dark patches' through star counts, polarimetry and colour gradients have generally given negative, ambiguous or doubtful results. The most recent study has been by Forte et al. (1992), who find a number of such patches in NGC 6624 and estimate a total dust mass of 0.07…0.8 $M_\odot$ in two regions, one some $20''$ and one some $110''$ from the cluster centre. This value could be consistent with the lack of detection by the IRAS survey (LR90), if the dust temperature at those distances were less than 20 K.

(ii) Mid IR. A general search of GCs in the IRAS Catalogs by LR90, and later of the IRAS Faint Source Catalog (Moshir et al. 1992) by Knapp, Gunn & Connolly (1995; hereafter KGC95), gave only upper limits for the intracluster dust, in the 0.001 to 0.01 $M_\odot$ range. This value depended on assuming a dust temperature T_d at the cluster cores of 50 K, using the calculations of Angeletti et al. (1982). LR90 found that there are many IRAS point sources near GCs, with over two thirds of clusters having such sources. But these sources were in the field and unrelated to the GCs, except for M 22 and NGC 2298. In the former case the planetary nebula in the cluster was detected (Gillett et al. 1986), with a temperature of 100 K and a mass of $10^{-3}\ldots10^{-2}$ $M_\odot$; in the latter case a very extended source exists. However neither of these detections relate to the problem of the general level of dust in the GCs. IRAS pointed observations of the cluster 47 Tuc (Gillett et al. 1988), with some 4000 seconds of observing, did find an excess of radiation at 100 μm, over that expected from the long-wavelength tail of the radiation from GC stars. The measured integrated excess of 0.12 ± 0.04 Jy leads to a dust mass of $3\,10^{-4}$ $M_\odot$.

2.3. Gas versus dust

Searches for gas have resulted in upper limits at levels usually above the searches for dust. The 0.001…0.01 $M_\odot$ limit for dust may be translated into corresponding limits on the mass of gas if a dust-to-gas ratio is assumed. The dust-to-gas ratio in the outflows of evolved field stars, both O- and C-rich, is in the range $4\,10^{-3}\ldots10^{-2}$ [see e.g. Whittet (1992) and references therein]. If we assume this value for GC stars we get upper limits on the mass of gas in the range 0.1…2.5 $M_\odot$. However the metallicity of GCs is considerably lower than it is for field stars and so this upper limit is a strong one.

3. Matter injection and removal

3.1. Injection

Significant mass loss only occurs after a star has evolved off the main-sequence. After this time, the star rapidly goes through a number of evolutionary states to end up as a white dwarf. The rate at which matter is injected into a cluster will thus depend solely on the rate at which stars evolve off the main-sequence and the amount of mass each star loses before it becomes a white dwarf.

3.2. Removal

Mechanisms proposed for the removal of intracluster matter from a GC may be intrinsic or extrinsic to the cluster. Several mechanisms have been proposed (see e.g. LR90, Smith et al. 1995 and references therein), although in the majority of cases the timescale for the mechanism to operate exceeds the time since the last crossing of the Galactic plane. We will re-assess these mechanisms in a later paper and for the present summarize the various mechanisms below.

3.2.1. Internal mechanisms

Mechanisms which are independent of the cluster environment include:

(i) removal by photoionized isothermal cluster winds;

(ii) heating by faint X-ray sources;

(iii) classical novae ejection. However recent observations of the remnant of the nova T Sco in the GC M80 (Shara & Drissen 1995) suggest that there may be fewer cataclysmic variables in GCs than had previously been estimated;

(iv) radiation pressure from the stars;

(v) kinetic ejection by hot and cold stellar and pulsar winds;

(vi) high speed of matter ejected from stars.

(vii) erosion of grains by X-rays from the X-ray sources in the clusters.

Table 1. Properties of M 3 and M 22. The sources of the figures are: Radii information – from Trager et al. (1995); Mass – from Pryor & Meylan (1993); [Fe/H] – from Kraft et al. (1995; M 3), Brown & Wallerstein (1992; M 22); D, distance from the Sun – Paez (1990) and Peterson & Cudworth (1994)

Cluster	Half-total-light radius		Tenth-total-light radius		Mass ($M_\odot$)	[Fe/H]	D (kpc)
M 3 (NGC 5272)	67″	(3.3 pc)	19″	(0.9 pc)	$6.3\,10^5$	–1.66	9.5±1.0
M 22 (NGC 6656)	199″	(2.9 pc)	85″	(1.2 pc)	$5.0\,10^5$	–1.75	2.6±0.3

Table 2. Upper limits on millimetre fluxes

Cluster	λ (μm)	Beam dia. (″)	On-source time (sec)	$3\,\sigma$ Flux Limit (mJy)
M 3	800	14	2485	21
M 22	1100	18	4000	17

3.2.2. External mechanisms

Mechanisms proposed for the removal of matter which are dependent on the cluster environment include:

(i) ram-pressure stripping by halo gas;

(ii) ejection by the integrated radiation pressure of Galactic stars;

(iii) erosion of grains by the hot x-ray emitting gas in the Galactic halo, either by sputtering by the atoms or by the X-rays from the gas.

4. Cluster orbits

A factor in determining the expected amount of interstellar matter injected into a GC is the time since it last passed through the Galactic plane. Knowledge of the details of the orbit (velocity, $Z-$distance from the Galactic plane and from the Galactic centre *versus* time) also allows the effects of external mechanisms which depend on a cluster's Galactic position and velocity to be determined.

Until recently, our knowledge of cluster orbits was limited to the information of its present position in the Galaxy and the radial velocity of the cluster. This enabled only the *minimum* time since the last Galactic plane crossing to be determined, as was done, for example by Tayler & Wood (1975). However, work in the last few years have measured the *absolute* proper motion of a number of clusters. Together with a mass model of the Galaxy, a radial velocity and proper motion enable the full orbit parameters to be determined for a cluster (see e.g. Dauphole et al. 1996, in press).

5. Observations and results

Two clusters, M 3 and M 22, were observed, at 800 μm and 1100 μm respectively. These clusters were chosen on the basis of their closeness and high mass. The salient properties of the clusters are given in Tables 1 and 3.

The observations were carried out using the He^3-cooled UKT14 bolometer on the James Clerk Maxwell Telescope (JCMT) on 1995 March 7th. Mars was used for flux calibration and pointing sources in the observatory catalogue were used to check pointing and focussing; pointing was accurate to 2″. Observations were made on GC centres, the positions of which were taken from Shawl & White (1986). The observations generally consisted of several sets of 50 20-sec cycles for M 3, and 20 50-sec cycles for M 22; the total on-source time was 2485 sec for M 3 and 4000 sec for M 22. The chop throw was 180″ at 4 Hz, with a beamsize as specified in Table 2. Neither cluster was detected, to the 3σ limits given in Table 2.

6. The orbits of M 3 and M 22

Scholz, Odenkirchen & Irwin (1993) measured the proper motion of M 3 relative to the extragalactic reference frame, which enables a true orbit to be calculated. For M 22, Cudworth & Hanson (1993) converted the relative proper motion of Cudworth (1986) to an absolute proper motion, using assumptions concerning the motion of the field stars and of the Sun, derived from the Lick absolute proper motion programme.

Using a galactic potential based on the mass model of Allen & Santillán (1991), orbits have been calculated for M 3, and M 22 and the resultant relevant orbit details are given in Tables 4 and 5. As the values for M 22 are derived using assumptions of the motions of field stars and the Sun, the orbit will be less certain than that calculated for M 3.

7. Discussion

7.1. Matter Injection for M 3 and M 22

A straightforward estimate of the rate at which stars are evolving off the main-sequence can be made by counting the number of horizontal branch stars in an annulus where crowding is not severe. A comparison of the total cluster light with the light in this annulus will then give the total number of horizontal-branch stars, which coupled with a knowledge of the horizontal-branch lifetime gives the rate of evolution. Tayler & Wood (1975) give figures for this present rate for M 3 and M 22. These are reproduced, in a different format, in Table 6.

The amount of mass lost by each star is the difference between its mass on the main-sequence and that of its final white dwarf state. The present mass of stars leaving the main-sequence is about 0.8 $M_\odot$ (see e.g. Bergbusch & VandenBerg 1992).

Table 3. Orbital properties of M 3 and M 22. The sources of the figures are: U, V, W, x, y, z, present space velocities and positions, in a right-handed Galactocentric Cartesian coordinate system with z pointing to the Galactic North Pole and x opposite to the Sun – from Scholz, Odenkirchen & Irwin (1993) and Cudworth & Hanson (1993)

Cluster	U	V (km s^{-1})	W	x	y (kpc)	z
M 3	–53±14	54±31	–108±4	–6.6±0.5	1.3±0.1	9.3±1.0
M 22	–148±5	194±19	–107±23	–5.5±0.5	0.43±0.04	–0.34±0.03

Table 4. Orbit of M 3. This table covers the period between the present and 115 Myr ago, when the cluster last passed through the Galactic plane. The x, y, z are space coordinates in a right-handed Galactocentric Cartesian coordinate system with z pointing to the North Galactic Pole and x opposite to the Sun. R is the distance from the Galactic centre

$Time$ (Myr)	x	y (kpc)	z	R
0	−7.10	1.25	9.30	11.77
−5	−6.81	1.00	9.81	11.98
−10	−6.47	0.73	10.25	12.14
−15	−6.09	0.47	10.62	12.25
−20	−5.67	0.20	10.91	12.30
−25	−5.22	−0.07	11.12	12.28
−30	−4.73	−0.34	11.25	12.21
−35	−4.22	−0.61	11.31	12.09
−40	−3.68	−0.87	11.28	11.90
−45	−3.12	−1.13	11.17	11.65
−50	−2.53	−1.38	10.97	11.34
−55	−1.93	−1.62	10.69	10.98
−60	−1.32	−1.85	10.31	10.56
−65	−0.69	−2.06	9.84	10.08
−70	−0.06	−2.26	9.27	9.54
−75	0.58	−2.43	8.59	8.95
−80	1.20	−2.58	7.81	8.31
−85	1.81	−2.69	6.90	7.62
−90	2.40	−2.76	5.86	6.91
−95	2.94	−2.79	4.68	6.19
−100	3.41	−2.74	3.35	5.51
−105	3.77	−2.62	1.87	4.96
−110	3.98	−2.39	0.23	4.65
−115	4.00	−2.04	−1.44	4.72

Richer et al. (1995) have determined a mass of 0.5 M$_\odot$ for the white dwarfs in M 4, giving a mass loss per star of about 0.3 M$_\odot$.

Over the time since the last plane crossing, the rate of evolution off the main-sequence, the mass of such stars, the time taken to reach the white dwarf stage, and the mass of the resultant white dwarfs are expected to have been relatively unchanged. For example, over 100 Myr, the mass of stars evolving off the main-sequence changes by $\lesssim$ 10^{-3} M$_\odot$ (e.g. Bergbusch & VandenBerg 1992). Thus, with little error, the present values can be taken as average values

The amount of dust injected into the clusters may be calculated if the division into gas and dust of the matter ejected by stars is known. The dust-to-gas ratio will depend on the mass and metallicity of the stars and their exact evolutionary stage when the mass-loss occurs. A good review of this is given by Gehrz (1989). Following the discussion in Sect. 2.3, we assume a typical value of 7 10^{-3} for the outflow of evolved stars, but scaled by the metallicity of the GCs relative to solar (cf. KGC95). We take scaling factors of 0.038 for M 3 and 0.027 for M 22, based on Kraft et al. (1995) and Brown & Wallerstein (1992) respectively. The total masses of gas and dust injected into the clusters are given in Table 6.

Table 5. Orbit of M 22. This table covers the period between the present and 3.56 Myr ago, when the cluster last passed through the Galactic plane. The columns are the same as in Table 4

$Time$ (Myr)	x	y (kpc)	z	R
0	−5.50	0.43	−0.34	5.52
−3.5	−5.03	−0.19	0.00	11.98

7.2. The conversion from flux to dust mass

Assuming that any dust emission at millimetre wavelengths is optically thin, we can write

$$S_\nu/\Omega = \tau_\nu B(\nu, T),$$

where S_ν is the flux density, Ω the beamsize, τ_ν the optical depth and $B(\nu, T)$ the Planck function at frequency ν and dust temperature T_d. Assuming a standard model for the distribution of stars in a GC, and that the dust is distributed in the cluster like the stars, the expected dust temperature is in the 40. . . 80 K range, depending on factors such as metallicity and grain emissivity (Angeletti et al. 1982). We assume three values of T_d here, the expected 40 K and 80 K, and also 20 K, to explore the possibility that the dust may be cold, as discussed by Forte et al. (1992).

The upper limits on the fluxes in Table 2 convert to upper limits on the optical depth, also listed in Table 7. The resultant dust mass is

$$\frac{M}{\mathrm{M}_\odot} = \frac{\pi a \rho}{3} \frac{\tau_\nu}{Q_\mathrm{abs}} D^2 \theta^2$$
$$= 4.1\ 10^{-8} \left(\frac{a}{0.1\ \mu\mathrm{m}}\right) \left(\frac{\rho}{3.5\ \mathrm{g\ cm}^{-3}}\right) \times$$

Table 6. Mass of gas and dust injected into the clusters since the last Galactic plane crossing. T - time since last Galactic plane crossing. The figures for the rate at which stars are evolving off the main sequence comes from Tayler & Wood (1975)

Cluster	T	Stars/Myr	Accumulated Mass ($M_\odot$)	
	Myr		Gas	Dust
M 3	110	5.1	170	$4.8\,10^{-2}$
M 22	3.56	3.7	3.9	$7.8\,10^{-4}$

$$\times \left(\frac{\tau_\nu}{10^{-6}}\right)\left(\frac{Q_{\rm abs}}{10^{-4}}\right)^{-1}\left(\frac{D}{\rm kpc}\right)^2\left(\frac{\theta}{\rm arcsec}\right)^2. \quad (1)$$

Here a is grain radius, ρ the bulk density of grain material, $Q_{\rm abs}$ the absorption efficiency of the grain material and θ the angular diameter of the beam.

The deduced dust mass is clearly sensitive to the dust absorption efficiency assumed. In this context we first note that the dust in the Galactic interstellar medium has suffered considerable processing by supernova shocks, mantle formation and polymerization etc. (Whittet 1992). As the dimensions of a GC are typically $\sim$ 10 pc, and the environment experienced by an interstellar grain in a GC is substantially different to that experienced by a grain in the Galactic interstellar medium, it seems plausible that the interstellar dust in GCs will bear little resemblance to 'standard' Galactic interstellar dust and may more likely resemble the pristine 'stardust' ejected by stars into the GC. Indeed, the typical distance between stars in the core of a GC is $\sim$ 0.1 pc, comparable with the dimensions of the circumstellar dust shell of an evolved star. Thus although we are searching for *interstellar* dust in GCs it may be argued that we should use the absorption efficiency appropriate to *circumstellar* dust. Unfortunately however the absorption efficiency of circumstellar dust at millimetre wavelengths is generally very poorly known, and is usually based on extrapolation from shorter wavelengths (e.g. Hoare 1990), or on millimetre observations of young (Gear, Robson & Griffin 1988) or highly evolved (Knapp, Sandell & Robson 1993) objects. Extrapolation requires assumptions about the $\beta-$index of the dust, defined by $Q_{\rm abs} \propto \nu^\beta$. For grains in the Galactic interstellar medium (e.g. Wright et al. 1991; Fischer et al. 1995), $\beta \simeq 1.5$, whereas $\beta \simeq 1$ for circumstellar dust (Knapp et al. 1993).

In their study of 47 Tuc Gillett et al. (1988) effectively assumed $Q_{\rm abs} \simeq 10.7\,a/\lambda$ (a, λ in μm) – appropriate to 'dirty silicate' – and extrapolated to 100 μm assuming β = 1; extrapolating to 1100 μm gives $Q_{\rm abs} \simeq 9.8\,10^{-4}$ for 0.1 μm grains. KGC95 used the well-known Hildebrand (1983) opacity, corresponding to $Q_{\rm abs} \simeq 1.2\,a/\lambda$ (a, λ in μm), significantly lower than the values used by Gillett et al. (1988). Extrapolating the Hildebrand opacity to 1000 μm assuming β = 1 gives $1.2\,10^{-4}$ for 0.1 μm grains. LR90 used Draine & Lee's (1984) optical constants for 1 μm silicate grains at the IRAS wavelengths; the Draine-Lee values for λ = 1000 μm are $Q_{\rm abs} = 1.34\,10^{-5}$ (silicate) and $Q_{\rm abs} = 2.08\,10^{-5}$ (graphite) for 0.1 μm grains (see also Draine 1985). The Draine-Lee values however were tailored to describe the optical properties of Galactic *interstellar* dust and, for reasons discussed above, may not be appropriate to GC grains. It may be argued that more reliable values follow from millimetre observations of evolved circumstellar envelopes and recently Knapp et al. (1993) have deduced $Q_{\rm abs} = 5.65\,10^{-4}$ (silicates) and $Q_{\rm abs} = 6.17\,10^{-4}$ (graphite) at 1100 μm, and unit $\beta-$index. We therefore calculate the dust masses using two values of $Q_{\rm abs}$, namely $6\,10^{-4}$ at 1100 μm (based on the millimetre observations and on 'dirty silicates [Gillett et al. 1988]), and $1.2\,10^{-5}$ at 1100 μm, based on the Draine (1985) values for silicate grains; we assume a $\beta-$index of unity.

The resulting upper limits on the dust mass are listed in Table 7, for three possible values of grain temperature, and the two assumed values of $Q_{\rm abs}(1100\,\mu{\rm m})$; in each case a grain radius a = 0.1 μm has been assumed. The limits on the dust mass derived from the lower $Q_{\rm abs}$ for M 3 in Table 7 may be compared with that obtained by KGC95, $\leq 3.1\,10^{-3} M_\odot$. The tightest limits found by LR90 were $M/M_\odot \leq 2.1\,10^{-3}$ (M 3) and $M/M_\odot \leq 1.5\,10^{-2}$ (M 22) for 1 μm grains and λ = 60 μm. On the other hand, our preferred value of $Q_{\rm abs}$ is similar to that used by Gillett et al. (1988) in their study of 47 Tuc, and our dust mass limits are comparable with their detection of $3\,10^{-4}\,M_\odot$ in 47 Tuc. However the $3\,10^{-4}\,M_\odot$ in 47 Tuc and our upper limits are all increased by a factor $\sim$ 50 with the Draine (1985) values of $Q_{\rm abs}$ but, for reasons already outlined above, we suggest that the higher values of $Q_{\rm abs}$ are more likely to be appropriate to GC dust.

We have used the upper limits on IR flux for M 3 and M 22 from LR90 and KGC95, converted them (where appropriate) to 3 σ flux limits and thence to 3 σ upper limits on mass, using the same $T_{\rm d}, a, \rho$ (40 K, 0.1 μm, 3.5 g cm^{-3} respectively) and

$$Q_{\rm abs} = 6.0\,10^{-4}\left(\frac{1100\,\mu{\rm m}}{\lambda}\right).$$

From LR90 we take the HCON1 flux limits that lead to the tightest upper limits on dust mass, which are for the 60 μm IRAS fluxes; we use the 100 μm data from KGC95. We then determine the limits on dust mass per unit area and per unit beam, so that upper limits obtained by the various methods can be directly compared on an equivalent basis. The IRAS beam is taken to be rectangular, $2' \times 2'$ at 60 μm for the HCON data (LR90), and $3' \times 4'$ at 100 μm (KGC95); in all cases the dust is assumed to be uniformly spread over the beam. The mass of dust per unit area and the mass of dust per beam follow directly from Eq. (1). The corresponding *equivalent* mass limits are given in Table 8.

It is apparent that the upper limits on dust mass from the present work are comparable with or, in the case of M 22, better than those deduced from IRAS data. On the other hand, while the upper limits *per unit area* and *per unit beam* derived from the present data are (again in the case of M 22) close to those obtained from the IRAS data, the corresponding IRAS limits for M 3 are much tighter than they are for the JCMT data. Comparison of the expected dust masses in Table 6 – calculated for the first time on the basis of reliable GC orbits – and the upper limits listed in Table 7 shows that we are now close either to

Table 7. 3 σ upper limits on optical depths and dust masses

Cluster	Q_{abs}[a]	τ_ν T_d = 80 K	T_d = 40 K	T_d = 20 K	$M/M_\odot$ T_d = 80 K	T_d = 40 K	T_d = 20 K
M 3	$6.0\,10^{-4}$	$6.0\,10^{-6}$	$1.4\,10^{-5}$	$3.5\,10^{-5}$	$5.3\,10^{-4}$	$1.2\,10^{-3}$	$3.1\,10^{-3}$
M 3	$1.2\,10^{-5}$				$2.7\,10^{-2}$	$6.0\,10^{-2}$	$1.5\,10^{-1}$
M 22	$6.0\,10^{-4}$	$5.4\,10^{-6}$	$1.2\,10^{-5}$	$2.8\,10^{-5}$	$8.1\,10^{-5}$	$1.8\,10^{-4}$	$4.2\,10^{-4}$
M 22	$1.2\,10^{-5}$				$4.1\,10^{-3}$	$8.8\,10^{-3}$	$2.1\,10^{-2}$

[a] At 1100 μm.

Table 8. Equivalent upper limits on dust mass

Cluster	Mass limits ($M_\odot$) LR90	KGC95	This paper	Mass limits area^{-1} (g cm^{-2}) LR90	KGC95	This paper	Mass limits beam^{-1} ($M_\odot$ sr^{-1}) LR90	KGC95	This paper
M 3	$8.6\,10^{-4}$	$2.3\,10^{-4}$	$1.2\,10^{-3}$	$5.9\,10^{-9}$	$5.3\,10^{-10}$	$7.6\,10^{-7}$	$2.5\,10^{3}$	$2.3\,10^{2}$	$3.3\,10^{5}$
M 22	$5.2\,10^{-3}$	–	$1.8\,10^{-4}$	$4.7\,10^{-7}$	–	$9.1\,10^{-7}$	$1.5\,10^{4}$	–	$2.9\,10^{4}$

detecting the dust in GCs, or to pushing the dust limits well below that expected on the basis of standard injection models. The present work also shows the considerable potential for pushing the mass limits down when our planned ISO observations of GCs are carried out, and when new sensitive bolometer arrays [such as SCUBA on the JCMT (Cunningham & Gear 1990)] become available on millimetre telescopes.

7.3. Distribution of dust

The chop throw of 180″ means that the reference positions were at radii comparable to the radii inside which half the cluster light is contained, as given in Table 1. If the dust distribution is smooth and concentric with the distribution of stars in the cluster, as in the models of Angeletti et al. (1982), and if the dust is distributed either like the stars or on a more compact scale, then the emission at the reference positions would be well below that at the cluster centres and should have been detectable. Thus for both clusters the size of the chop should have been adequate.

However, the projected beams of the JCMT (radii of 0.33 pc for M 3 and 0.11 pc for M 3) were significantly smaller than the scales of the light distribution, so if the dust is distributed like the stars then much of the dust will be outside our beam. However, there are arguments to suggest that any dust will be concentrated to the cluster core, see e.g. Angeletti et al. (1982). Thus while it is possible that there is more dust in the cluster than our upper limits imply, this is not necessarily the case.

If there is dust in these clusters but it does not lie at the cluster centres, as proposed by Forte et al. (1992) for NGC 6624, then again this search would miss it. If by chance the dust was located in the reference position instead of at the cluster core, a negative signal would be found; however no such negative signals were obtained.

8. Conclusions

The limits we have obtained on the dust content of the GCs M 3 and M 22 are comparable to the implied dust mass in 47 Tuc (Gillett et al. 1988), and are somewhat lower than previous limits for other clusters. Although these results refer only to the cluster core, they reinforce previous conclusions that the dust mass in GCs is significantly less than expected if no significant removal mechanisms are occurring. Thus for M 3 we expect 1.2 $M_\odot$ of dust (Table 6), but find less than 0.00053. . . 0.0031 $M_\odot$ (Table 7) for the most plausible temperature range and Q_{abs}.

The dust must thus have been destroyed, expelled, hiding in a non-centrally concentrated location, or extremely cold ($\lesssim$ 20 K).

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