

LETTER TO THE EDITOR

The *Herschel* Virgo Cluster Survey

III. A constraint on dust grain lifetime in early-type galaxies[★]

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Received 29 March 2010 / Accepted 30 April 2010

ABSTRACT

Passive early-type galaxies (ETGs) provide an ideal laboratory for studying the interplay between dust formation around evolved stars and its subsequent destruction in a hot gas. Using *Spitzer*-IRS and *Herschel* data we compare the dust production rate in the envelopes of evolved AGB stars with a constraint on the total dust mass. Early-type galaxies which appear to be truly passively evolving are not detected by *Herschel*. We thus derive a distance independent upper limit to the dust grain survival time in the hostile environment of ETGs of $<46 \pm 25$ Myr for amorphous silicate grains. This implies that ETGs which *are* detected at far-infrared wavelengths have acquired a cool dusty medium via interaction. Given likely time-scales for ram-pressure stripping, this also implies that only galaxies with dust in a cool (atomic) medium can release dust into the intra-cluster medium.

Key words. galaxies: elliptical and lenticular, cD – galaxies: ISM – infrared: galaxies

1. Introduction

In this paper we compare the dust outflow rate from the evolved AGB stars in passive ETGs, with the total dust mass, to estimate dust grain lifetimes. Both quantities are derived from observations; the outflow rate from *Spitzer*-IRS spectra, and the total dust mass from *Herschel* (Pilbratt et al. 2010) maps of the

Herschel Virgo Cluster Survey, HeViCS (Davies et al. 2010, www.hevics.org). We assume that evolved stars are the only source of dust in these passive systems as there is very little evidence that type Ia supernovae produce dust.

IRAS data have been used in the past in a similar way. Soifer et al. (1986) estimated the mass-loss from evolved stars in the bulge of M 31 from 12 and 25 μm fluxes and the total dust mass from the 60 and 100 μm fluxes. They concluded that given that the observed dust mass could be produced by stellar outflows in only 10^7 yr, there must be some mechanism that depletes the bulge of inter-stellar matter. Jura et al. (1987) made similar

[★] *Herschel* is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.

calculations for a sample of elliptical galaxies. They estimated dust outflow rates by assuming that half of the $12\ \mu\text{m}$ flux came from dusty stellar envelopes. They also found that the stellar mass-loss rate would be sufficient to produce the observed cool ISM in much less than a Hubble time.

Dust mass production rate and total dust mass can only reasonably be compared in objects that are truly passively evolving. Temi et al. (2007) find, that for a given blue luminosity, the 70 and $160\ \mu\text{m}$ luminosities vary by 2 orders of magnitude, indicating that many ETGs have a significant dust component not directly attributable to mass-loss from evolved stars. For our purposes, these ETGs are not “passive” because other processes (mergers?) have probably contributed to the dust mass.

Recent studies of ETGs with *Spitzer* (Bressan et al. 2006; Clemens et al. 2009) have shown that even in samples of ETGs selected to be the most passive objects (i.e. lying on the colour-magnitude relation) a significant fraction show evidence of either on-going or recent past star formation. These results indicate that ETGs in which dust features are seen in the optical (e.g. Sadler & Gerhard 1985) and many that have been detected by IRAS at 60 and $100\ \mu\text{m}$ (Knapp et al. 1989) and *Spitzer* at 70 and $160\ \mu\text{m}$ (Kaneda et al. 2007) may also host low levels of star formation. Intriguingly, of the 7 ellipticals detected at 70 and $160\ \mu\text{m}$ by Kaneda et al. (2007) the only object not showing PAH emission features is actually a radio source, so that the far-infrared emission is probably synchrotron!

Tsai & Mathews (1995) studied dust destruction in ETGs via thermal sputtering in the hot (10^6 – 10^7 K), low density ($n_{\text{H}} \sim 0.1\ \text{cm}^{-3}$) gas, and found that the destruction time-scale is short compared to any cooling flow or dust transport time-scale. They therefore concluded that dust is destroyed “on the spot” before it has time to migrate within a galaxy. In a following work, Tsai & Mathews (1996) found dust-to-gas mass ratios that are orders of magnitude less than that in typical stellar ejecta or in the ISM of the Milky Way. Their interpretation of the IRAS data was, at that time, hampered by the resolution of the existing observations; they were therefore not able to tie down the origin and distribution of the observed dust emission.

As part of the *Herschel* science demonstration phase (SDP), a $4 \times 4\ \text{deg}^2$ field, centred approximately on M 87, has been observed as part of the HeViCS with both the PACS (Poglitsch et al. 2010) and SPIRE (Griffin et al. 2010) instruments. See Davies et al. (2010) for details.

2. Results

Bressan et al. (2006) observed a sample of ETGs in the Virgo cluster with *Spitzer*-IRS. The objects were selected to lie on the optical colour-magnitude relation and were expected to be passively evolving objects. The mid-infrared spectra for this sample showed that only 76% were actually passive objects, with the remainder showing signs of either on-going or recent past star formation (PAH features) or AGN activity (atomic lines). Of this sample of 17 galaxies, 9 lie in the HeViCS SDP field. 6 of these show IRS spectra consistent with passively evolving stellar populations (with the possible exception of NGC 4371), and it is these 6 objects, listed in Table 1, on which we base our study.

2.1. Dust mass detection limit

Of the 6 passive ETGs in the HeViCS SDP field, none are detected at any wavelength (100, 160, 250, 350 and $500\ \mu\text{m}$)¹.

¹ We note that several ETGs are detected in the SDP field, including M 87, M 84, M 86, NGC 4459, NGC 4435 and NGC 4550, but none of these are truly passively evolving.

Because of the sensitivity of the emission at the shorter PACS wavelengths to small masses of relatively warm dust, we consider only the SPIRE images at 250, 350 and $500\ \mu\text{m}$ to determine the dust mass detection limit.

Our mass detection limit depends on whether we consider the detection of an extended or point source. For passive galaxies, the dust should follow the stellar distribution, and thus be strongly centrally peaked. As the core radius of an elliptical galaxy at the distance of the Virgo cluster is typically less than the resolution of the SPIRE images (respectively $18''$, $25''$ and $37''$) the most likely detection would take the form of a point source.

Unless the dust is very cold ($\lesssim 17$ K) the tightest limit on the dust emission comes from the $250\ \mu\text{m}$ map. This has a point source detection limit of $S_{\text{rms}} = 9.6$ mJy. We calculate the dust mass detection limit as (Hildebrand 1983):

$$M_{\text{d}} \leq \frac{S_{\text{rms}}(\nu)D^2}{\kappa_{\text{d}}(\nu)B(\nu, T_{\text{d}})} \quad (1)$$

where D is the distance to the Virgo cluster (16.5 Mpc, Mei et al. 2007) and $\kappa_{\text{d}}(\nu)$ is the dust mass opacity coefficient. The value of $\kappa_{\text{d}}(\nu)$ depends on the grain composition but the mid-infrared spectra (Sect. 2.2) are consistent with pure silicate grains. For dust composed only of amorphous silicate grains $\kappa_{\text{d}}(250\ \mu\text{m}) = 0.6517\ \text{m}^2\ \text{kg}^{-1}$ (Draine & Lee 1984). Adopting this value, and $T_{\text{d}} = 30$ K, we arrive at a 2σ mass detection limit of $M_{\text{d}} \leq 8.7 \times 10^3 M_{\odot}^2$.

2.2. Dust production rate from AGB stars

Assuming a spherically symmetric, stationary stellar wind of velocity v_{∞} , and dust mass-loss rate $\dot{M}_{\text{d}}^{\text{CE}}$ the circumstellar dust density is,

$$\rho_{\text{d}}^{\text{CE}} = \frac{\dot{M}_{\text{d}}^{\text{CE}}}{4\pi r^2 v_{\infty}} \quad (2)$$

The optical depth of the circumstellar envelope, τ , is obtained by multiplying Eq. (2) by the dust opacity coefficient and integrating from r_{in} to r_{out} , where the former is the dust sublimation radius and the latter is a convenient outer radius $\gg r_{\text{in}}$. We thus have,

$$\tau_1 = \frac{\dot{M}_{\text{d}}^{\text{CE}} \kappa_1}{4\pi v_{\infty} r_{\text{in}}} \quad (3)$$

where κ_1 is the dust opacity at $1\ \mu\text{m}$, following the notation of Bressan et al. (1998), and we have neglected the very small term $1/r_{\text{out}}$. The dust sublimation radius is $r_{\text{in}} \propto L^{1/2}$ (Granato & Danese 1994) and the proportionality constant depends mainly on the dust composition (through its sublimation temperature), the size distribution and only weakly on the shape of the stellar spectrum. Inserting the value of r_{in} into Eq. (3) we obtain,

$$\dot{M}_{\text{d}}^{\text{CE}} = A \tau_1 v_{\infty} \sqrt{L_4} \quad (4)$$

where L_4 is the bolometric luminosity in units of $10^4 L_{\odot}$. The factor A is mainly determined by the dust mixture. For the mixture of silicate grains of M-type AGB stars used in Bressan et al. (1998), suitable for the spectra of passive ETGs (Fig. 1), $A \approx 6.5 \times 10^{-10} M_{\odot} \text{yr}^{-1}/(\text{km s}^{-1})$.

² Were the dust composed of amorphous carbon (Serra Diaz-Cañó & Jones 2008) then $\kappa_{\text{d}}(250\ \mu\text{m}) = 1.932$ (Rouleau & Martin 1991) and the mass detection limit $M_{\text{d}} \leq 2.9 \times 10^3 M_{\odot}$.

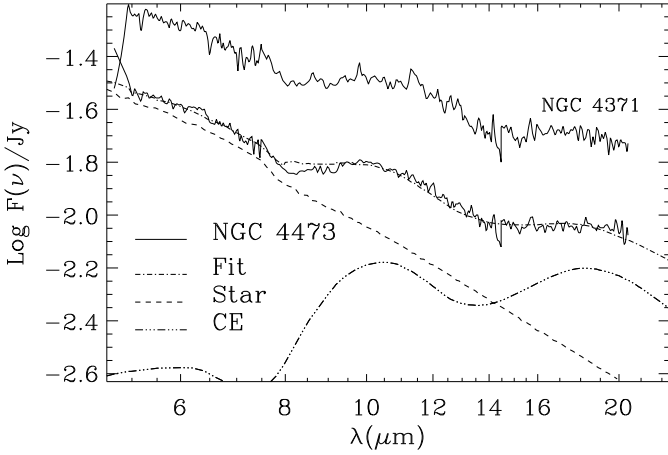


Fig. 1. *Spitzer*-IRS spectrum of NGC 4473. The fitted model components are the stellar photosphere, and dusty circumstellar envelope (CE). The spectrum of NGC 4371 is shifted by 0.2 dex.

Table 1. Dust mass loss rates and grain lifetimes, t_g .

NGC	$\dot{M}_d/L_V(K)^\dagger$	\dot{M}_d/M^\ddagger	$\dot{M}_d(\text{beam})$	t_g^*
	$\frac{M_\odot \text{ yr}^{-1}}{10^{26} \text{ W Hz}^{-1}}$	$\frac{M_\odot \text{ yr}^{-1}}{10^{12} M_\odot}$	$10^{-4} M_\odot \text{ yr}^{-1}$	10^6 yr
4371	3.80	0.00855	1.0	86
4442	3.48	0.00712	1.7	51
4473	3.57	0.00742	1.9	46
4474	3.71	0.00806	0.59	150
4551	2.61	0.00468	0.36	240
4564	4.28	0.00959	1.3	65

Notes. (*) For an assumed dust temperature of 30 K. (†) The specific dust mass-loss rate per unit K -band luminosity. (‡) The mass loss per $10^{12} M_\odot$ of galaxy mass. A dust mass opacity coefficient suitable for amorphous silicate grains has been used.

To determine the dust mass-loss rate from the MIR spectrum we fit a combination of a pure photospheric atmosphere, a MARCS model (Gustafsson et al. 2008) of 4000 K, plus the emission from a dusty envelope selected from the library of Bressan et al. (1998), as described in Bressan et al. (2007). We thus obtain the fraction of flux, say at $10 \mu\text{m}$, $f_d^{\text{slit}}(10 \mu\text{m})$, due to dusty circumstellar envelopes, and, from the distance of the galaxy, the corresponding “dust” luminosity sampled by the slit, $4\pi D^2 f_d^{\text{slit}}(10 \mu\text{m})$.

Surprisingly, though ETGs contain a mixture of evolved stars of different metallicity and age, a single dusty envelope is typically enough for a good fit to the MIR spectrum.

The shape of the broad feature near $10 \mu\text{m}$ in general requires $\tau_1 \sim 2\text{--}4$, and so the envelopes are optically thin at $10 \mu\text{m}$. From the shape of the $10 \mu\text{m}$ feature we thus derive the optical depth of the “average” AGB star. To compute its dust mass-loss rate through Eq. (4) we need to assume a bolometric luminosity and wind velocity. Typical values for evolved, old stars are $L_d \sim 0.2\text{--}0.4$ and $v_\infty \sim 5\text{--}15 \text{ km s}^{-1}$.

The total dust mass-loss sampled by the slit is finally obtained by multiplying the value for the “average” AGB star by the number of dusty AGB stars sampled by the slit. This is given by the ratio of the dust luminosity of the galaxy to that of the

Table 2. Parameter values for calculation of grain lifetime and the power of their dependence on the derived lifetime.

S_{rms}	$\kappa_d(250)$	T_d	A^*	τ_1	v_∞	L_d
mJy	$\text{m}^2 \text{ kg}^{-1}$	K	10^{-10}		km s^{-1}	$10^4 L_\odot$
9.6	0.6517	30	6.5	fit	10	0.3
1	–1	–1 [†]	1	1	1	0.5

Notes. E.g., $t_g \propto 1/T_d$. (*) The units of A are $M_\odot \text{ yr}^{-1}/(\text{km s}^{-1})$. (†) In the Rayleigh-Jeans limit; which is a bad approximation for $T_d \lesssim 20 \text{ K}$.

“average” AGB star, $L_d^{\text{CE}}(10 \mu\text{m})$. Thus, the total dust mass-loss sampled by the slit is,

$$\dot{M}_d^{\text{slit}} = A \tau_1 v_\infty \sqrt{L_d} \frac{4\pi D^2 f_d^{\text{slit}}(10 \mu\text{m})}{L_d^{\text{CE}}(10 \mu\text{m})}. \quad (5)$$

Summarizing, the spectral fit provides τ_1 and $f_d^{\text{slit}}(10 \mu\text{m})$. From τ_1 , which characterizes the dusty envelope, and the assumed bolometric stellar luminosity, we obtain $L_d^{\text{CE}}(10 \mu\text{m})$ and finally \dot{M}_d^{slit} , for a specified value of v_∞ . We note that, since $L_d^{\text{CE}}(10 \mu\text{m})$ scales approximately with the bolometric luminosity of the star, the total mass-loss has only a weak dependence on the assumed luminosity of the typical AGB star.

We finally note that recent work (Boyer et al. 2010) has shown dust to be released into the ISM only by AGB stars, contrary to some claims that RGB stars also contribute.

2.3. Dust grain lifetimes

Dust mass-loss rates were derived from *Spitzer*-IRS spectra that were taken through a slit of dimensions $18'' \times 3''.6$ centred on the galaxy. In order to compare these values with the dust masses within one $250 \mu\text{m}$ beam we assume that the light distribution in the mid and far-infrared are similar, and that both are similar to that at K -band. For each galaxy, we use the 2MASS K -band image, smoothed to the *Spitzer*-IRS spatial resolution, to determine the flux within the IRS slit. We then smooth the K -band image to the *Herschel* $250 \mu\text{m}$ resolution and calculate the flux within one beam. We use the ratio of these two fluxes to derive the mass-loss rate from the area of one *Herschel* beam.

We derive dust grain lifetimes simply as the ratio of dust mass detection limit to dust mass-loss rate, M_d/\dot{M}_d . Our dust mass detection limit of $M_d \leq 8.7 \times 10^3 M_\odot$ for silicate grains results in grain lifetimes as given in Table 1. The tightest constraint, of $<46 \pm 25 \text{ Myr}$, is provided by NGC 4473. The error reflects the uncertainties in v_∞ and L_d . In Table 2 we provide the values used to arrive at this grain lifetime and their dependencies. For dust temperatures in the range 20–40 K, for example, the grain lifetime lies in the range 69–31 Myr.

If dust grains are destroyed via sputtering in the $10^6\text{--}10^7 \text{ K}$ gas in ETGs then the theoretically, *expected* dust grain lifetime in years is $t = k_i r_g/n_H$ (e.g., Tielens et al. 1994), where r_g is the grain radius in nm, n_H is the gas density in cm^{-3} and $k_i = 310$ for silicate dust (210 for amorphous carbon, 1500 for graphite) so the grain lifetime should be longer in galaxies with a lower density hot ISM.

Of our sample, NGC 4371 and NGC 4474 both lie in the least X-ray luminous category as defined by Irwin & Sarazin (1998). NGC 4564 has been observed by Chandra, and the central hot gas density estimated to be $0.011 \pm 0.006 \text{ cm}^{-3}$ by Soria et al. (2006). These authors analyzed a sample of “quiescent” galaxies and found central gas densities in the range

0.011–0.03 cm⁻³. These values overlap with the low end of estimates from Chandra data of more general ETG samples (Pellegrini 2005). We thus assume a hot gas density of 0.02 cm⁻³ for all our ETGs. The expected dust grain lifetime, for “typical” 100 nm silicate grains is 1.55 Myr (1.05 for amorphous hydrocarbon, 7.5 for graphite) and thus consistent with our non-detections.

3. Discussion and conclusions

We interpret the ratio of dust mass to dust production rate as a measure of grain lifetime. In principle, however, dust could be removed from the galaxy rather than destroyed.

A wind of hot gas produced by type Ia supernovae probably cannot drive dust (or gas) out of the potential well of massive ETGs (Mathews & Loewenstein 1986). However, good evidence of ram-pressure stripping of the hot ISM in elliptical galaxies has been found in the form of X-ray tails (Randall et al. 2008; Machacek et al. 2006). If dust is found in this hot gas then it too may be removed. However, the timescale for such stripping is estimated to be of the order a few 10⁸ yr (Takeda et al. 1984; Murakami & Babel 1999, Eq. (12)) which is an order of magnitude longer than our upper limit to the grain lifetime. The observation that the X-ray emission of most ETGs is *not* displaced from the stellar distribution, in fact, suggests that either the stripping time-scale is longer than the hot gas production time-scale or that the ram-pressure is typically insufficient to remove the hot medium. It is now clear that if dust is isolated from the hot medium in denser, cooler clouds, than ram-pressure does have time to strip dust (Cortese et al. 2010) but the passive ETGs in our study do not show any evidence of accumulating dust in such clouds. *Passive* ETGs do not directly pollute the intra-cluster medium with dust.

Grain lifetimes of <46 Myr have immediate implications for ETGs that *are* detected in the FIR. Either they produce dust at rates much higher than those given in Table 1 or their dust is shielded from the hot gas in cool clouds. For example, the dust mass of NGC 4435 of $1.2 \times 10^6 M_{\odot}$ would require a total dust production rate of 0.03 $M_{\odot} \text{ yr}^{-1}$, more than an order of magnitude greater than any value in Table 1. This object is known to host star formation (Panuzzo et al. 2007) and so dust is likely to be in cool clouds more typical of late-type galaxies; grain lifetimes in this case may be much longer. Dust may have been acquired from an interaction, but in any case it probably arrived as part of a cooler medium.

In a passive ETG, the ISM, and the dust within it, come mainly from mass-loss from evolved stars. Unless the dust-to-gas ratio in this released material is very variable, one would expect dust and gas production to follow one another. If the X-ray luminosity, $L_x \propto n_e^2$, one would naively expect a relation $L_x \propto M_d^2$. However, if the grain lifetime, $t_g \propto 1/n_H$, then we would expect only a linear correlation between L_x and M_d . Kaneda et al. (2007) find evidence of an *anti-correlation* for a small sample of elliptical galaxies detected by *Spitzer*-MIPS, but this may be expected if the dust were of external origin.

Only NGC 4371 is detected by MIPS at 70 μm (marginally at 160 μm). The detection is consistent with our *Herschel* detection limits. This object actually shows extremely weak PAH features in its *Spitzer*-IRS spectrum, and is therefore probably not totally passive. The object is included for comparison, and its IRS spectrum included in Fig. 1.

We have assumed that AGB stars are the only source of dust. Were type Ia supernovae able to produce dust from the metals they produce, we estimate that the contribution to the dust production rate would be, at most, similar to that of AGB stars. Our limit on grain lifetime would be a factor of ~ 2 lower in this case.

Although dust grains are rather short-lived in ETGs, the prospects for survival in the intra-cluster medium are rather better because the gas densities are typically at least 2 orders of magnitude lower than in ETGs (Böhringer et al. 1994). Therefore, if dust can be removed from cluster galaxies, or form in the intra-cluster medium, there is a good chance that such dust will be detected by the HeViCS, especially at larger cluster radii where gas densities are lower.

Acknowledgements. M.C. and A.B. acknowledge support from contract ASI/INAF I/016/07/0.

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