Cold Interstellar Dust in Elliptical Galaxies: Evidence for Energetic Processes in the Galactic Cores

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ABSTRACT

Far-infrared observations of elliptical galaxies show spatially extended, excess dust in several otherwise normal elliptical galaxies. The mass of extended dust exceeds that expected from our steady state models in which normal dusty mass loss from evolving red giant stars is balanced by grain destruction by sputtering. In at least one galaxy, NGC 5044, the extended excess dust is asymmetrically distributed in radial plumes previously known to contain enhanced X-ray and optical line emission. The astronomical implications of this unexpected excess dust are far-reaching and provide important new information about AGN feedback to the hot interstellar gas. These observations provide qualitatively new information about AGN-related energy released by central black holes and the buoyant transport of AGN-heated dusty gas in the hot gas atmospheres associated with massive elliptical galaxies.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: ISM — infrared: galaxies — infrared: ISM — ISM: dust, extinction — ISM: structure

1. Observations and Models

Our recent observations of elliptical galaxies with *ISO* and *Spitzer* (Temi et al, 2004, 2007a, 2007b) have revealed that the far-infrared luminosity L_{FIR} from these galaxies can vary by ∼100 among galaxies with similar optical luminosity. This amazing scatter in far-IR

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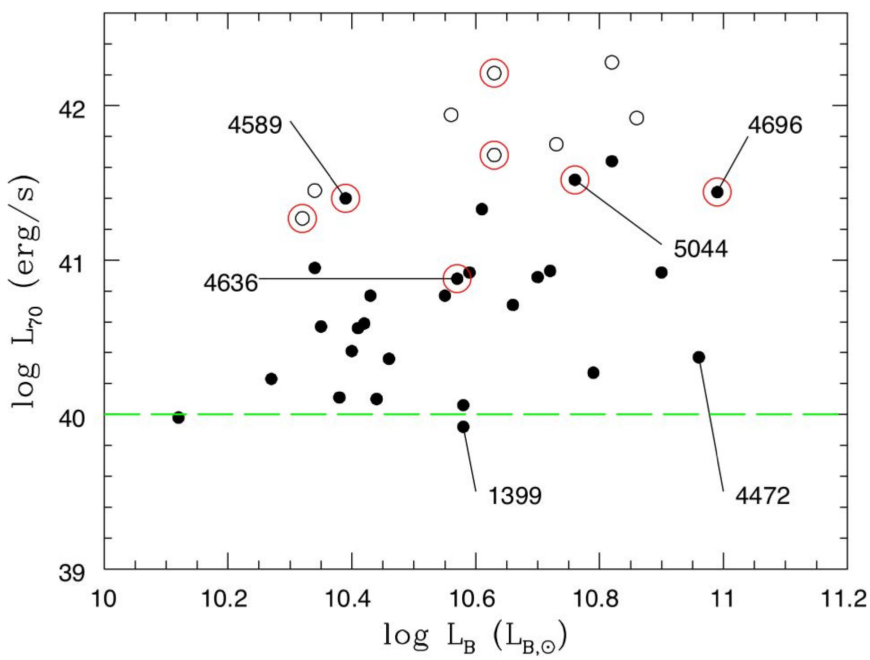

Fig. 1.— Plot of Spitzer 70 μm luminosity against L_B for elliptical galaxies. Green dashed line shows emission only from local dust-producing red giant stars. Small filled circles are normal galaxies, but open circles denote unusual post-merger galaxies with unusually large masses of cold gas. Large red circles indicate spatially extended 70 μm.

luminosity ranges from galaxies with relatively low L_{FIR}, in which current local stellar mass loss can explain the observed infrared emission, to ellipticals containing large excess masses of dust and cold gas that almost certainly result from significant galaxy mergers in the past. Between these extreme limits, however, we find many optically normal elliptical galaxies, having no evidence of recent merger activity, but which nevertheless contain spatially extended dust (out to 5-10 kpc) that far exceeds that ejected from old, mass-losing red giant stars into the local ISM. These are the galaxies of most interest. To assess the mass of dust required to explain observed 70 and 160 μm fluxes, we first estimate the steady state dust mass expected from normal local dusty stellar mass loss. In (Temi et al. 2007a) we developed the following simple theoretical model for in situ dust evolution in elliptical galaxies:

(1) Mid-IR emission follows the starlight profile, indicating that this is circumstellar dust around old mass-losing red giant stars for which the collective mass loss rate is known reasonably well and the dust/gas mass ratio is normalized to the local stellar metallicity at each galactic radius. We assume dust grains from the stars have a standard Milky Way size distribution. (2) When the dusty gas becomes interstellar and encounters the hot gas, it rapidly achieves pressure equilibrium in the hot gas and warms to $\sim 10^4$ K, heated by UV

from post-main sequence stars.

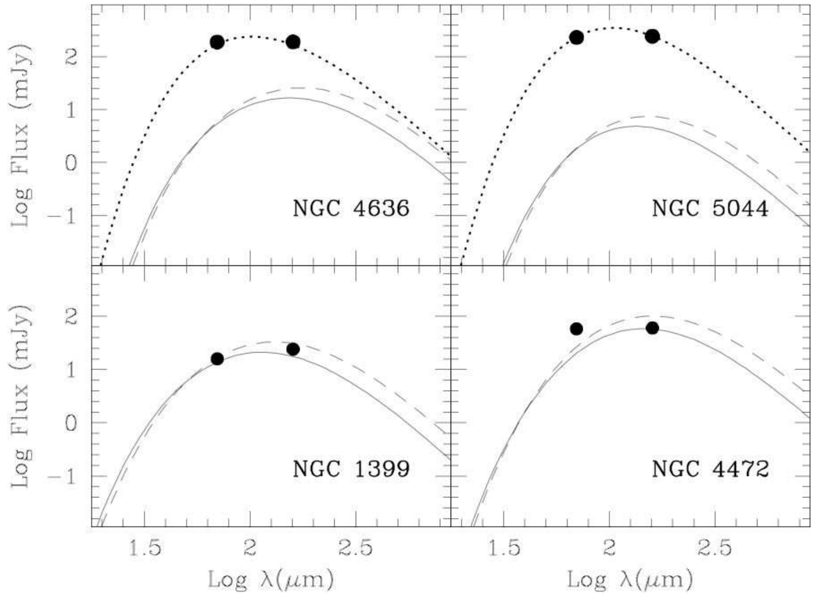

Fig. 2.— Spitzer observations of four galaxies at 70 and 60 μm (filled circles), compared with estimated model SEDs due to dust produced by local stellar mass loss (the short-dashed and solid lines are for grain size distributions extending to a_{max}= 1 and 0.3 microns respectively). Models with excess dust masses $10^5 M_{\odot}$ extending to $\sim$ 5 kpc in NGC 4636 and 5044 are shown with dotted lines. (Temi et al. 2007b).

(3) Diffuse optical emission from this warm (10^4 K) gas is seen in the majority of elliptical galaxies, but the relatively low global H_{β} fluxes indicates that the warm gas must be rapidly heated by thermal conduction and thermalized with the hot gas in $< 10^6$ years, when the dust becomes directly exposed to the hot gas. (4) Dust in hot gas is erosively destroyed (sputtered) by ion impacts in $\sim 10^7$ yrs at 10 kpc, altering the grain size distribution. (5) During their brief lifetimes, the dust grains emit far-IR radiation easily detectable with Spitzer. Amorphous silicate grains are heated by absorption of starlight and by inelastic collisions with thermal electrons. This latter process is unique to the hot gas environment and requires that we know the hot interstellar gas density and temperature profiles from Chandra and XMM data. (6) The far-IR emissivity at each galactic radius is found by integrating over the local grain size (and therefore temperature) distribution. (7) When the emissivity is integrated over the galaxy, we can calculate the galactic spectral energy distribution (SED) and the far-IR luminosity. For a typical luminous elliptical we find $L_{70} \sim 10^{40}$ergs/s at 70 μm

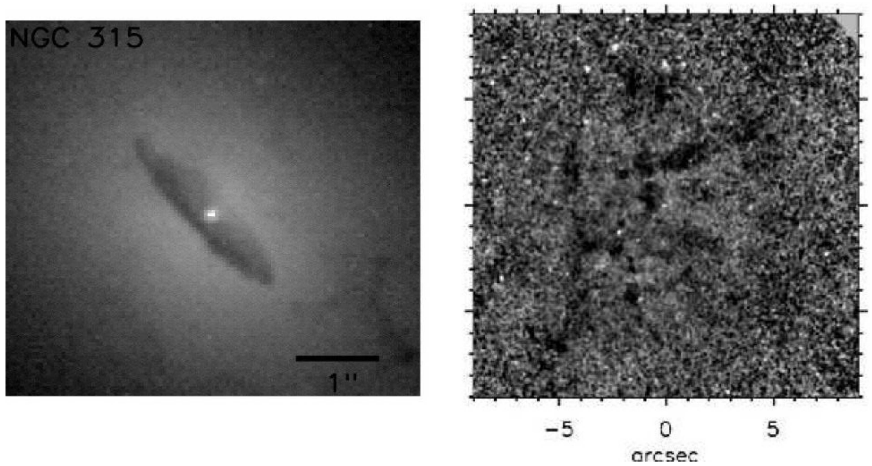

Fig. 3.— HST images of the central kpc of NGC 315 (left), showing dusty disk with outlying faint clouds, and NGC 5044 (right), showing transiently accelerated dense dusty clouds.

2. Discussion

As seen in Figure 1 elliptical galaxies with the lowest L_{70}/L_B do in fact have $L_{70} \sim 10^{40}$, as we predict. We believe that this agreement indicates that our theoretical far-IR SEDs are correct to within a factor of ~ 2 or better. In Figure 2 we see that the observed far-IR fluxes in two galaxies with the lowest L_{70}/L_B – NGC 1399 and 4472 agree very well with our theoretical steady state SEDs. But it is quite amazing that many ellipticals have L_{70}/L_B that exceed our estimate, some by as much as ~ 100. Many of the most IR luminous E galaxies, however, are known to have large disks of neutral or molecular hydrogen – which almost certainly result from a merger event These galaxies are indicated in Figure 1 with small open circles. However – and this is most remarkable – many perfectly normal ellipticals (filled circles in Figure 1) have L_{70} that are 10 – 30 times in excess of model predictions but show no evidence of mergers within the short sputtering lifetime of the dust, $\sim 10^7$ yrs. If this extended cold dust is internally produced, the most likely source of internal dust is in the galactic cores. HST images (as in Figure 3) show that at least half of all massive elliptical galaxies are known to have dust clouds or disks within a few 100 parsecs of their centers (van Dokkum& Franx 1995; Lauer et al. 2005).

We propose that the extended cold dust observed in ellipticals with originates in these small, often kinematically disturbed disks/clouds in galactic cores. If all the nuclear dust were accreted onto the black hole, the AGN luminosity would exceed the bolometric X-ray emission from the most luminous galaxy groups and poor clusters. Since $L_{acc} >> L_X$, there is more than enough energy to shut down the cooling flows. It is more likely however that

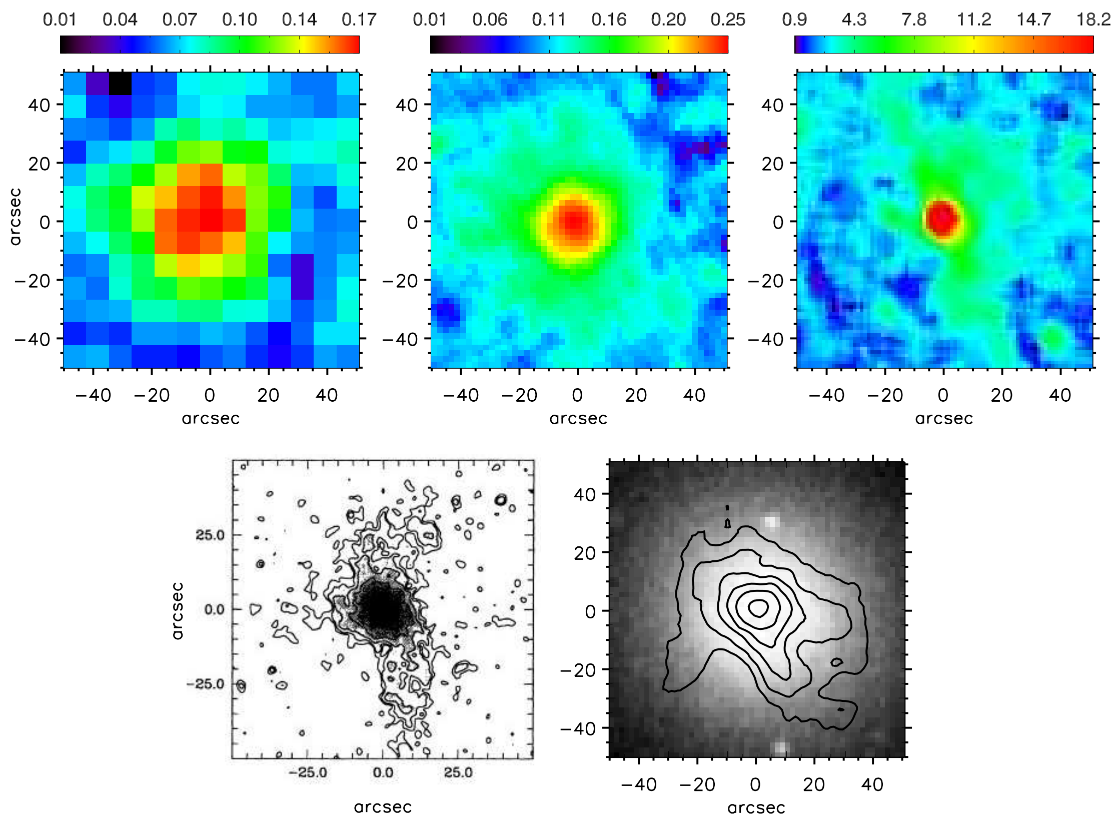

Fig. 4.— Comparison of optical, infrared and X-ray emission from NGC 5044. The physical scale is 160 parsecs / ”. The top three panels from left to right show Spitzer images at 160, 70, and the difference image [8-4.5] microns. The bottom panels show from left to right isophotes of Halpha+[NII] emission from warm gas in NGC 5044 taken from Goudfrooij et al. (1994) and isophotes from the Chandra X-ray images superimposed on an optical image from the Digital Sky Survey.

only a fraction of the dusty gas is accreted and the rest is AGN-heated and transported in buoyant gaseous plumes out to $\sim 5 - 10$ kpc in the hot interstellar gas where the dust is ultimately consumed by sputtering. The [8-4.5] μm difference image of NGC 5044 reveals asymmetric spatial extensions that are closely coincident with highly asymmetric warm gas emission at $H_\alpha + [NII]$ observed optically out to $\sim$ 6 kpc (Figure 4). We interpret the extended mid-infrared emission as 8 μm PAH emission and we expect that these plumes will also be visible at 70 μm in a deeper exposure. Moreover, the dust can cool the subsonically rising hot buoyant gas in about $\sim 10^7$ yrs, explaining the optical line emission seen out to 5 kpc. The hot gas is cooled very efficiently by inelastic collisions between grains and thermal electrons. Consequently, much of the vertical scatter in Figure 1 at intermediate L_{70} is due to diffuse dust that traces the inherent intermittancy of AGN feedback. The lack of gas rich galaxies close to (or merging with) these ellpticals, and ellipticals in general, does not support the hypothesis that the vertical scatter in Figure 1 results from a stochatic supply of external dust from recent mergers as formerly thought. But mergers may nevertheless occur in some cases, particularly for E galaxies with the largest L_{70}/L_B in Figure 1 and we remain open to this interpretation. For a typical dust/gas mass ratio 0.01, we expect that dust accumulates in elliptical galaxy cores to form the typical nuclear dust mass $\sim 10^5 M_\odot$ in only $\sim 10^8$ yrs. Why are the central dust masses so small? We speculate that after $\sim 10^7 - 10^8$ yrs, an energetic AGN outburst occurs when some of the dusty gas is accreted. At this time the unaccreated nuclear dusty gas is heated and buoyantly removed, explaining why nuclear dust clouds are not observed in 40% percent of luminous ellipticals. The astronomical implications of the creation of dusty nuclear clouds/disks, accretion of these clouds onto central black holes, AGN energy release, and buoyant outflow of the dust, are directly related to understanding the energetics of the hot gas that have been proposed as a likely solution of the so-called cooling flow problem: why the hot interstellar gas emits X-radiation but is not observed to cool to intermediate or low temperatures. This is just the type of "feedback" heating that is required to explain the maximum stellar mass of elliptical galaxies and their observed deficiency or absence of continuing star formation. The buoyant outflow we describe here is similar to our computed flows that successfully resolve the cooling flow problem with the outward transport of both mass and energy from the galactic core to large radii, i.e. A circulation flow (Mathews, Brighenti & Buote 2004).

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