RAPID COOLING OF DUSTY GAS IN ELLIPTICAL GALAXIES

WILLIAM G. MATTHEWS1 AND FABRIZIO BRIGHENTI1,2
Received 2002 August 6; accepted 2003 May 5; published 2003 May 13

ABSTRACT

We propose a stellar origin for the central dust clouds observed in most giant elliptical galaxies. Dusty gas ejected from evolving red giant stars in elliptical or cD galaxies can cool rapidly even after entering the hot X-ray-emitting gas. Cooling by thermal collisions with dust grains can be faster than either the dynamical time in the galactic potential or the grain sputtering time. Some grains survive in the cooled gas. Dusty stellar outflows cool more efficiently in the central regions, where the stellar metallicity is higher. Mergers with gas and dust-rich dwarf galaxies may occasionally occur but are not required to explain the observed dust clouds.

Subject headings: cooling flows — dust, extinction — galaxies: clusters: general — galaxies: elliptical and lenticular, cD — X-rays: galaxies — X-rays: galaxies: clusters

1. INTRODUCTION

While most of the interstellar gas mass in elliptical galaxies, typically \( \sim 10^7 \, M_\odot \), is at the galactic virial temperature \( T_{\text{vir}} \sim 10^7 \, \text{K} \), the cores of \( \sim 80\% \) of all large elliptical (E) galaxies contain dusty clouds of cold gas of mass \( \leq 10^4–10^5 \, M_\odot \) (e.g., van Dokkum & Franx 1995). In addition, diffuse optical line emission from gas at \( T \sim 10^4 \, \text{K} \) is observed in most or all elliptical galaxies within a few hundred parsecs from the center (e.g., Caon, Macchetto, & Pastoriza 2000), particularly in those galaxies formerly thought to contain “cooling flows.” The notion that the hot gas cools to low temperatures is not supported by XMM spectra (e.g., Peterson et al. 2001; Xu et al. 2001), i.e., the observed cooling rate \( \dot{M} \) is lower than that expected in traditional cooling flows, \( \sim 1 \, M_\odot \, \text{yr}^{-1} \). In any case, cooling of essentially dust-free hot gas cannot produce dust clouds. In the following, we propose that the dusty clouds are formed from gas expelled from evolving metal-rich red giant stars in E galaxy cores. Even if these dusty stellar envelopes are heated to \( \sim T_{\text{vir}} \) after leaving the stars, the gas can cool rapidly by collisions between thermal electrons and dust grains.

2. COOLING-SPUTTERING EVOLUTION

Direct evidence that mass is being lost from evolving stars in X-ray–luminous elliptical galaxies is provided by near-IR (\( \sim 10 \, \mu m \)) observations of hot circumstellar dust (Knapp et al. 1989, 1992; Athey et al. 2002). The 9.7 \( \mu m \) peak from (oxygen-rich) silicate grains apparent in Infrared Space Observatory (ISO) observations places an upper limit on the grain radius, \( a \leq 1 \, \mu m \) (Fig. 5 of Laor & Draine 1993). According to Athey et al., the total luminosity of excess near-IR radiation is consistent with expected total stellar mass-loss rates in giant E galaxies, \( \sim 1 \, M_\odot \, \text{yr}^{-1} \).

However, as dusty gas moves away from orbiting mass-losing red giant stars, it encounters the hot interstellar gas at \( T \sim T_{\text{vir}} \sim 1 \, \text{keV} \) and is violently disrupted by hydrodynamic instabilities. The interaction of the stellar wind/planetary nebula with the hot gas is extremely complicated, but this ejected gas cannot remain at \( T \sim 10^4 \, \text{K} \) for more than \( t_{\text{vir}} \sim 10^7 \, \text{yr} \) without exceeding the typical H\( \alpha + [\text{N}\,\text{ii}] \) luminosities observed (Matthews & Brighenti 1999). XMM spectra show no evidence for slowly heating gas at \( T \leq T_{\text{vir}}/2 \). This empirical evidence supports rapid thermal mixing of the stellar ejecta, which is probably a consequence of gas-dynamical instabilities that enormously increase the surface area between the stellar ejecta and the ambient hot gas. In view of the complexity of this interaction, the thermal evolution \( T(t) \) of gas ejected from stars is difficult to estimate, but limits can be set. In the following discussion, we adopt a useful limiting assumption for \( T(t) \): the dusty gas is rapidly heated to the temperature of the local hot gas with the dust intact.

This assumption maximizes the likelihood that the stellar gas will remain thermally merged with the hot gas phase. Grain sputtering during the rapid heating process is unlikely, since the heating time must be \( \leq t_{\text{vir}} \), which is very much less than the sputtering time (see below).

When dust grains are introduced into a hot plasma with \( T \approx 3 \times 10^4 \, \text{K} \), they are sputtered (eroded) by impacting thermal H\( ^+ \) and He\( ^{+2} \) ions. The grain radius \( a \) decreases at a rate

\[
\frac{da}{dt} = -n_p n_a \left[ 1 + \left( \frac{T_a}{T} \right)^{2.5} \right]^{-1} \text{cm s}^{-1}
\]

(Draine & Salpeter 1979; Tsai & Mathews 1995), where \( n(\text{He}^{+}) = n(\text{H}^{+})/10 \). Here \( n_p = 3.2 \times 10^{-18} \, \text{cm}^3 \, \text{s}^{-1} \) and \( T_a = 2 \times 10^8 \, \text{K} \) are fitting parameters, \( n_p = n_p(4 - 3\mu)/(2 + \mu) \) is the proton density, and \( \mu = 0.61 \) is the molecular weight. We assume for simplicity that the cooling occurs at constant gas pressure \( P \), so \( n_a = (2 + \mu)P/5kT \).

As soon as the dusty gas is heated (by assumption) to the local gas temperature, it will begin to cool. Cooling occurs by thermal X-ray emission from the gas and by inelastic impacts of thermal electrons with the grains. Grain-electron cooling can greatly exceed that from thermal X-ray emission (e.g., Dwek 1987; Dwek & Arendt 1992), provided the grains are not sputtered away. If the cooling time is shorter than the dynamical time in the galactic potential, the gas will tend to cool approximately in situ, the case we consider here. During isobaric cooling, the gas temperature decreases according to

\[
\frac{dT}{dt} = -\frac{2}{5} \frac{T}{P m_p^2} (\Lambda + \Lambda_a) = -\frac{2}{5} \frac{\mu}{k} P \frac{\Lambda + \Lambda_a}{T}.
\]

Here \( \Lambda(T, z) \) is the usual thermal radiation coefficient for gas
radius in microns. At pressures of interest, \( P_{\text{atm}} = P/(10^{-10} \text{ dyn}) \), the plasma mean free path, \( \lambda \approx 0.02 T_{\text{pl}}^{1/2} \text{ cm} \), is small; only electrons in the cooling regions collide with the grains; electrons from the hot ambient gas thermalize in the cooling plasma before colliding with a grain. In NGC 4472, a giant elliptical in the Virgo Cluster that we use for reference, \( n_e \approx 0.0551 r_{e,1.1}^{-1.1} \text{ cm}^{-3} \), so \( e_e = 7.7 \times 10^{-7} a_e^2 \) and \( 7.3 \times 10^{-12} a_e^2 \) at \( r = 1 \text{ kpc} \) and the effective radius \( r = R_e = 8.57 \text{ kpc} \), respectively. We adopt a distance of 17 Mpc to NGC 4472.

Grains can internally absorb the energy of thermal electrons, provided \( E_e \leq E_r = 23\alpha_{\text{Fe}}^{-1} \text{ keV} \) (Dwek & Werner 1981), which we assume is generally satisfied. Cooling by electron impact on grains during the sputtering time, \( t_s \approx a_t/d\text{d}a_t/dt \approx 1.2 \times 10^7 a_t (n_e/(10^{-7}))^{-1} \text{ yr} \), greatly exceeds the additional gas cooling required to fully ionize the grain atoms ejected in the sputtering process or to bring these sputtered ions up to local thermal velocities.

At any moment the space density of interstellar grains \( n_e \) in luminous elliptical galaxies is very inhomogeneous, being concentrated near mass-losing stars. If \( m_e \) is the total mass of the stellar envelope ejected by evolving stars, the density of (silicate) grains, then the total number of grains expelled by a single star is \( N_e = \delta m_e / (4/3)\pi a_e^3 \), where \( \delta \) is the ratio of the dust mass to the gas mass when ejected from the stars.

We assume that \( \delta = 0.01 z_{\text{Fe}} \) decreases with stellar metallicity as in NGC 4472, where \( z_{\text{Fe}} \approx 0.675 (r/R_e)^{-0.207} \) in solar units (Brighteni & Mathews 1999).

The initial space density of grains is proportional to the local gas density \( n_{e,0} = (N_e/m_e)_0 \). As the gas cools isobarically from some initial temperature \( T_{e,i} \), the grain space density increases, \( n_e = n_{e,0} T_e/T \approx [(\delta m_e / (4/3)\pi a_e^3)(\mu \text{Plk})/T] \). The dust cooling coefficient in equation (2), \( \Lambda_d = n_e \dot{e}_e/\rho a_e^2 \), is then

\[
\Lambda_d = \frac{9}{8} + \frac{2}{5} \mu \left( \frac{8}{\pi m_e} \right)^{1/2} \frac{\delta m_k}{a_e} \frac{T_{e,i}}{\rho a_e^{3/2}} \text{ ergs cm}^{-3} \text{ s}^{-1}.
\]  

To explore the influence of grain cooling, we integrate equations (1) and (2) beginning with gas at temperature \( T_0 = T_{e,i} \) and pressure \( P(r) \) at galactic radius \( r \) in the hot gaseous atmosphere of NGC 4472. The pressure \( P = n_e(r)kT(r)/5(2 + \mu) \) is constant during cooling. For simplicity, we assume that the gas is filled with grains all having the same initial radius \( a_e \). As the gas cools, the sputtered debris from the grains increases the metallicity of the gas phase. To evaluate the plasma cooling rate coefficient \( \Lambda(T, z) \) during the cooling, we assume that the gas-phase metal abundance in solar units increases with decreasing grain mass \( \approx a_0 \).

\[
\approx 1 - (a_0/\text{a}) \delta d_{\text{max}},
\]

where \( \delta_{\text{max}} \approx 0.053 \) is the maximum ratio of dust to gas mass if all elements heavier than He were in grains.

3. RESULTS

We describe solutions of equations (1) and (2) for the elliptical galaxy NGC 4472 with initial conditions at radii \( r = 1 \) and \( r = R_e = 8.57 \text{ kpc} \). According to our assumption, the dusty gas expelled from a star is rather quickly heated to the local temperature of the hot gas at these two galactic radii, \( T_0 = 0.95 \times 10^7 \text{ and } 1.16 \times 10^7 \text{ K} \), where the gas density is \( n_{e,0} = 6.52 \times 10^{-2} \text{ and } 4.45 \times 10^{-3} \text{ cm}^{-3} \), respectively. Figures 1a and 1b show the combined evolution of the gas temperature \( T(t) \) and grain radius \( a(t) \) for grains of initial radius \( a_e = 1 \text{ and } 0.1 \mu \text{m} \), assuming \( \delta = 0.01 \) and \( \delta = 0.0064 \) at \( r = 1 \text{ and } r = 8.57 \text{ kpc} \), respectively. For comparison, we also
plot the cooling curve $T(t)$ of dust-free gas ($a_0 = 0\mu$) with the same $T_0$ and $n_{eo}$.

Dust-enhanced cooling can reduce the cooling time of recently ejected gas by over an order of magnitude compared to the dust-free case. For fixed $\delta$, the ratio $\Delta_\delta/\Delta$ increases rapidly with decreasing grain radius $a_0$ because of the larger total surface area of smaller grains.

A defining characteristic of cooling flows is that the isobaric radiative cooling time $t_{\text{cool}, \text{rad}} = 5m_p kT/2\mu_\Lambda \approx 10^5 t_{\text{rad}}^2$ yr (in NGC 4472) exceeds the dynamical time $t_{\text{dy}} \approx \sqrt{GMr} \approx 10^7 t_{\text{rad}}^{3/2}$ in the galactic potential. Dust-free moderately positive density perturbations do not cool appreciably faster than unperturbed regions. If overdense regions remain coherent, they oscillate radially in the hot gas atmosphere, becoming underdense relative to the ambient gas during half their cycle (e.g., Loewenstein 1989).

The dust-rich regions that we describe here are not initially in an overdense state but become overdense as the cooling proceeds. The dust-rich gas cools locally if the cooling time is less than the dynamical time at the two selected galactic radii, $t_{\text{dy}} = 2.1 \times 10^6$ at $r = 1$ kpc and $1.2 \times 10^7$ yr at 8.57 kpc. Figures 1a and 1b show that $t_{\text{cool}} < t_{\text{dy}}$ is possible at $r = 1$ kpc, so gas at small galactic radii can cool to low temperature and also preserve a small amount of its original dust since $t_{\text{cool}} < t_{\text{dy}}$. The cooling curves in Figures 1a and 1b are independent of $m_\nu$ and are therefore unchanged if the dusty envelope is disrupted or fragmented during its interaction with the hot gas. We show one case in Figure 1b in which dusty gas with $a_0 = 0.1 \mu$ begins cooling at $T_e/3$, before fully thermalizing with the hot gas. The cooling time is significantly reduced, confirming our assumption that maximizes the cooling time.

As dust-rich stellar winds flow away from orbiting red giant stars, the winds are decelerated by interactions with the local hot gas, but the grains, impelled by their higher momentum, can move into the ambient gas. It is possible in principle that the ejected dust cloud occupies and cools a gas mass larger than that ejected from the star, $m_\nu$. If the cooled mass exceeds $m_\nu$ by a factor of $\omega$, then the corresponding cooling evolution is found simply by replacing $\delta$ in equation (4) with $\delta\omega$. In Figure 1c, we show cooling curves for $\omega = 2$ at the same two galactic radii for grains of initial radius $a_0 = 0.1 \mu$. Both cooling times exceed the dynamical time at the galactic radii considered, so the cooling gas may have a more complex dynamical evolution that may inhibit the cooling.

4. DISCUSSION AND CONCLUSIONS

Stellar mass loss has been regarded as an important internal source of hot gas within group- or cluster-centered E galaxies. A $\sim 13$ Gyr old stellar population of total mass $M_\star$ typically expels $M_\star \sim 1.5(M_\star/10^{12} M_\odot) M_\odot$ yr$^{-1}$. In cluster-centered galaxies, such as M87 in Virgo and NGC 4874 in the Coma Cluster, the gas temperature rapidly decreases in the central $\sim 15$ kpc from the virial temperature of the cluster (3–8 keV) to the stellar virial temperature $\sim 1$ keV at $r \approx 3$ kpc (Molendi 2002; Vikhlinin et al. 2001). Detailed gasdynamical models of traditional cooling inflows in these cluster-centered galaxies indicate that this steep temperature gradient can be understood only if gas is being cooled by thermalization of stellar ejecta (Brighenti & Mathews 2002b). The increase in the hot gas oxygen abundance toward the center of M87 (Gastaldello & Molendi 2002) is expected if mass lost from the Type II supernova–enriched stars has thermally mixed into the hot interstellar medium and if the stars are more O-rich than the Virgo Cluster gas. Nevertheless, we propose here that the dust component can cool the stellar ejecta soon after it thermally merges with the ambient hot gas, particularly at $r \leq 1$ kpc.

We now review how dust-enhanced cooling applies to the issues discussed in § 1:

1. What is the source of interstellar dust observed in the cores of $\sim 80\%$ of all large E galaxies? Van Dokkum & Franx (1995) and others describe small central dust disks, lanes, or clouds typically a few 100 pc in size. The small masses of dust $\leq 10^{-5} M_\odot$ in these cores can be easily produced in $\sim 10^4–10^5$ yr as dust-rich gas cools near the Galactic center with incomplete sputtering. It is difficult to accurately estimate the rate that dust accumulates near the center without knowledge of the dust size distribution, the exact thermal history $T(t)$ of the stellar ejecta, or the star formation rate in the cold, dusty clouds. Since Type Ia supernova remnants occupy a very small fraction of the interstellar volume at any time (Mathews 1990), heating by Type Ia supernovae is unlikely to interfere with the cooling that we describe here. Heating by active galactic nuclei has often been suggested to explain why the hot gas in E galaxies fails to cool to low temperatures (e.g., Rosner & Tucker 1989; Binney & Tabor 1995; Brighenti & Mathews 2002a). If such heating occurs, it must be gentle enough not to destroy the observed central dust clouds or this dust must be rapidly regenerated.

2. What is the source of the diffuse optical line emission ($H\alpha + [N \text{ ii}]$) observed in most or all cooling flow galaxies? The velocities of this diffuse emission are unrelated to stellar velocities (Caon et al. 2000). In some E galaxies, the optical line emission spatially correlates with X-ray features (e.g., Trinchieri & Goudreau 2002) or traces the perimeters but not the centers of X-ray cavities (McNamara, O’Connell, & Sarazin 1996; Blanton, Sarazin, & Irwin 2001). While these observations suggest that some gas cools to $\sim 10^4$ K from the hot phase, there is no evidence for this in XMM X-ray spectra. However, even if dusty gas ejected from metal-rich stars is heated to $\sim T_e$, it can quickly cool back to $\sim 10^4$ K, where the cooling may be temporarily arrested by absorption of galactic UV starlight (Binette et al. 1994). Exactly what happens next is unclear, but the dust can help cool the gas to much lower temperatures if the clouds become optically thick to UV radiation. It has often been suggested that dusty gas at $T \sim 10^4$ K derives from mergers with gas-rich dwarf galaxies (e.g., Caon et al. 2000; Trinchieri & Goudreau 2002); this can be verified if the $10^4$ K gas is counterrotating. Nevertheless, cold, dusty gas can arise naturally from stars in E galaxy cores.

3. Why is the observed cooling rate $M$ from X-ray observations so low? Xu et al. (2001) found from reflection grating spectrometer XMM observations of elliptical galaxy NGC 4636 that X-ray lines expected from gas cooling near $T < 2 \times 10^4$ K are unusually weak, indicating a total cooling rate of $M \leq 0.30 M_\odot$ yr$^{-1}$ in $r < 2.5$ kpc (for $d = 17$ Mpc). Far Ultraviolet Spectroscopic Explorer observations of O vi lines in NGC 4636 (emitted at $T \sim 3 \times 10^4$ K) indicate $M \approx 0.17 \pm 0.02 M_\odot$ yr$^{-1}$ within 1.2 kpc (Bregman et al. 2001). Both cooling rates are less than the $\sim 1–2 M_\odot$ yr$^{-1}$ predicted in traditional cooling flow models (e.g., Bertin & Tonazzo 1995).

Rapid dust-assisted cooling may be relevant to this discrepancy in two ways: (1) by reducing the total rate that gas enters the hot phase and (2) by reducing the X-ray emission from cooling thermal gas at subvirial temperatures. In models of traditional cooling flows, gas ejected from stars is usually assumed to enter the hot interstellar gas. The stellar mass-loss
rate in a giant E galaxy, \( \sim 1 \, M_\odot \, yr^{-1} \), is an important source of gas, since it is comparable to the expected cooling rate of the hot gas. In gasdynamical models, the cooling rate \( \dot{M} \) near the center of the flow varies inversely with the specific rate of stellar mass loss, \( \dot{M}_* = M_{*,c} / M_* \). This is true even when there is an extended reservoir of circumgalactic hot gas due to cosmic accretion onto the surrounding galaxy group. Therefore, the apparent cooling rate \( \dot{M} \) observed with XMM should be reduced approximately in proportion to the fraction of stellar gas that fails to enter the hot gas because of dust-assisted cooling.

However, if more than \( \sim 90\% \) of the stellar ejecta fails to enter the hot phase, our gasdynamical models indicate that the density of hot interstellar gas is lowered sufficiently to initiate a strong galactic wind driven by Type Ia energy. The transition to wind flows is rather sudden. Since the very low \( L_\chi \) characteristic of strong winds is not observed, this sets a limit on the efficiency of dust-assisted cooling described here.

If dusty gas from stars is indeed heated to \( \sim T_{\text{vir}} \), XMM observations require that it not emit thermal X-rays at intermediate temperatures either as it is heated or as it cools afterward. We argue above that the heating phase is likely to be rapid, \( \lesssim t_{\text{he}} \sim 10^3 \, yr \). When heated to \( \sim T_{\text{vir}} \), the stellar gas may undergo rapid dust-assisted cooling, during which the X-ray emission from intermediate temperatures is greatly reduced. The radiation expected from an X-ray line of emissivity \( \epsilon_{\text{line}}(T, \rho) \) ergs s\(^{-1}\) g\(^{-1}\), \( \dot{E}_{\text{line}} = \int \epsilon_{\text{line}}dT/|dT/dt| \) ergs g\(^{-1}\), varies inversely with the cooling rate \( |dT/dt| \), which can be \( \geq 10 \) times larger than normal plasma cooling. The X-ray line emission is suppressed by a similar factor.

In dust-assisted cooling, much of the thermal energy in the hot gas is radiated by dust in the far-IR (FIR). The maximum FIR luminosity expected, \( L_{\text{FIR}} \sim 5MK^2/2\mu_{\nu} \sim 2 \times 10^{44} (T/10^7) \times (M/M_\odot \, yr^{-1}) \) ergs s\(^{-1}\), is consistent with ISO FIR luminosities observed in NGC 4472 and NGC 4636, \( \nu L_{\nu} \lesssim 2 \times 5 \times 10^{41} \) ergs s\(^{-1}\) (Temi et al. 2003).

Nevertheless, it seems unlikely that dust-enhanced cooling can explain the weakness of X-ray cooling lines from gas at subviral temperatures in clusters (e.g., Peterson et al. 2001) where the expected cooling rates, \( M \gtrsim 100 \, M_\odot \, yr^{-1} \), greatly exceed the stellar mass-loss rate in the central E or cD galaxy.

Studies of the evolution of hot gas in elliptical galaxies at UC Santa Cruz are supported by NASA grants NAG5-8049 and ATP02-0122-0079 and NSF grants AST 98-02994 and AST 00-98351, for which we are very grateful. F. B. is supported in part by grants MURST-Cofin 00 and ASI-ARS99-74.

REFERENCES

Athey, A., Bregman, J., Bregman, J., Temi, P., & Sauvage, M. 2002, ApJ, 571, 272
Bertin, G., & Toniazzo, T. 1995, ApJ, 451, 111
Binette, L., et al. 1994, A&A, 292, 13
Binney, J., & Tabor, G. 1995, MNRA, 276, 663
Blanton, E. L., Sarazin, C. L., & Irwin, J. A. 2001, ApJ, 552, 106
Bregman, J. N., Miller, E. D., & Irwin, J. A. 2001, ApJ, 553, L125
Brighenti, F., & Mathews, W. G. 1999, ApJ, 515, 542
———. 2002a, ApJ, 567, 130
———. 2002b, ApJ, 573, 542
Caon, N., Macchetto, D., & Pastoriza, M. 2000, ApJS, 127, 39
Draine, B. T., & Salpeter, E. E. 1979, ApJ, 231, 77
Dwek, E. 1987, ApJ, 322, 812
Dwek, E., & Arendt, R. G. 1992, ARA&A, 30, 11
Dwek, E., & Werner, M. W. 1981, ApJ, 248, 138
Gastaldello, F., & Molendi, S. 2002, ApJ, 572, 160
Knapp, G. R., Guhathakurta, P., Kim, D.-W., & Jura, M. A. 1989, ApJS, 70, 329
Knapp, G. R., Gunn, J. E., & Wynn-Williams, C. G. 1992, ApJ, 399, 76
Laor, A., & Draine, B. T. 1993, ApJ, 402, 441
Loewenstein, M. 1989, MNRAS, 238, 15
Mathews, W. G. 1990, ApJ, 354, 468
Mathews, W. G., & Brighenti, F. 1999, ApJ, 526, 114
McNamara, B. R., O’Connell, R. W., & Sarazin, C. L. 1996, AJ, 112, 91
Molendi, S. 2002, ApJ, 580, 815
Peterson, J. R., et al. 2001, A&A, 365, L104
Rosner, R., & Tucker, W. H. 1989, ApJ, 338, 761
Sutherland, R. S., & Dopita, M. A. 1993, ApJS, 88, 253
Temi, P., Mathews, W. G., Brighenti, F., & Bregman, J. D. 2003, ApJ, 585, L121
Trinchieri, G., & Goudreault, P. 2002, A&A, 386, 472
Tsai, J. C., & Mathews, W. G. 1995, ApJ, 448, 84
van Dokkum, P. G., & Franx, M. 1995, AJ, 110, 2027
Vikhlinin, A., et al. 2001, ApJ, 555, L87
Xu, H., et al. 2002, ApJ, 579, 600