WHERE DO COOLING FLOWS COOL?

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ABSTRACT

Typically, ~5% of the total baryonic mass in luminous elliptical galaxies is in the form of cooled interstellar gas. Although the mass contributed by cooled gas is small relative to the mass of the old stellar system in these galaxies, it is almost certainly concentrated within the optical effective radius where it can influence the local dynamical mass. However, the mass of cooled gas cannot be confined to very small galactic radii ($r \lesssim 0.01 r_e$) since its mass would greatly exceed that of known central mass concentrations in giant ellipticals, normally attributed to massive black holes. We explore the proposition that a population of very low mass, optically dark stars is created from the cooled gas. For a wide variety of assumed radial distributions for the interstellar cooling, we find that the mass of cooled gas contributes significantly (~30%) to stellar dynamical mass-to-light ratios which, as a result, are expected to vary with galactic radius. However, if the stars formed from cooled interstellar gas are optically luminous, their perturbation on the mass-to-light ratio of the old stellar population may be reduced. Cooling mass dropout also perturbs the local apparent X-ray surface brightness distribution, often in a positive sense for centrally concentrated cooling. In general, the computed X-ray surface brightness exceeds observed values within $r_e$, suggesting the presence of additional support by magnetic stresses or non-thermal pressure. The mass of cooled gas inside $r_e$ is sensitive to the rate at which old stars lose mass $M_e$, but this rate is nearly independent of the initial mass function of the old stellar population. 

Subject headings: cooling flows — galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: ISM — X-rays: galaxies

1. INTRODUCTION

Perhaps the most perplexing and long-standing problem associated with galactic and cluster cooling flows is the uncertain physical nature and spatial distribution of the gas that cools. The apparent absence of large masses of cooled gas in elliptical galaxies has led some to argue that little or no cooling actually occurs and to postulate some source of heating that offsets the radiative losses in X-ray emission. But the energy required to balance radiative losses is prohibitively large, and appropriate heating sources may not be universally available. If the expected radiative cooling actually occurs, two questions arise: (1) What is the nature of the objects that condense from the hot gas? and (2) Where is most of the cooled mass located in the galaxy? Regarding the first question, a variety of physical arguments support the hypothesis, or even the inevitability, of low-mass star formation (Fabian, Nulsen, & Canizares 1982; Thomas 1986; Cowie & Binney 1977; Vedder, Trester, & Canizares 1988; Sarazin & Aske 1989; Ferland, Fabian, & Johnstone 1994; Mathews & Brighenti 1999). Here we shall address the second question in the context of cooling flows in elliptical galaxies where the known stellar mass and light profiles strongly constrain the spatial distribution of cooled gas.

We adopt the generally accepted hypothesis that only stars of very low mass (e.g., $\lesssim 0.1 M_\odot$) form in cooling flows (e.g., Ferland et al. 1994), so that the mass-to-light ratio of the young stellar population formed from the cooling gas is essentially infinite. In view of the difficulties we encounter with this hypothesis, described below, it seems more likely that the stellar population formed from cooled gas extends to somewhat more massive stars that are optically luminous.

Our gasdynamical models for the evolution of hot interstellar gas in giant ellipticals indicate that the origin of the gas varies with galactic radius. Most of the gas in the inner, optically luminous regions originates from the ejected envelopes of evolving stars; gas in the outer halo is supplied by cosmological secondary infall or tidal acquisitions from neighboring galaxies (Mathews & Brighenti 1998b). Circumgalactic gas around massive ellipticals is enriched by Type II supernovae (SN II) that accompanied early star formation. The variability of circumgalactic gas among luminous ellipticals is responsible for some of the enormous dispersion in X-ray luminosity $L_X$ among ellipticals of similar optical luminosity $L_B$ (Mathews & Brighenti 1998a).

Since the hot interstellar gas in a bright elliptical emits observable X-rays, it is clearly losing energy. However, as the gas loses energy it is compressed toward the galactic center by gravitational forces and $P dv$ work maintains the high temperatures observed, $T \sim 10^7$ K, producing a galactic cooling flow. The positive interstellar temperature gradients typically observed within a few effective radii are often cited as evidence of radiative cooling in a cooling flow, but this cooling is instead due to the mixing of somewhat cooler, locally virialized gas ejected from stars with hotter gas arriving from larger galactic radii (Mathews & Brighenti 1998b; Brighenti & Mathews 1998, 1999a). If large entropy fluctuations are present in the hot gas, catastrophic cooling can occur at any radius in the flow. Regions of low entropy (low temperature, high density) radiate more and cool sooner. The amplitude distribution of entropy fluctuations in the interstellar gas determines the radius where cooling mass dropout occurs in the cooling flow. For example, if the entropy in some region in the flow is only slightly less than in the ambient flow, the differential radi-
ative cooling will be small and the region will cool out of the flow at small galactic radii; conversely, localized regions with entropy much lower than the ambient flow cool rapidly and deposit their mass at large radii. Some possible sources of interstellar entropy variations are stellar winds, explosions of Type Ia supernovae (SN Ia), nonuniform SN II heating at early times, and mergers with small, gas-rich galaxies.

The total rate at which mass cools and drops out of the flow is closely related to the X-ray luminosity $L_X$. The X-ray luminosity can be approximately expressed as the product of the total cooling rate $\dot{M}$ and the enthalpy per gram in the hot gas, or

$$\dot{M} = \left(\frac{2\mu m_p}{5kT}\right) L_{X,\text{bol}} \approx 2.5 \, M_\odot \text{ yr}^{-1}.$$ 

Here we have used data from the giant Virgo elliptical NGC 4472: $T \approx 1.3 \times 10^7$ K; $L_X(0.5-4.5$ keV) = $4.5 \times 10^{41}$; $L_{X,\text{bol}} \approx 1.6L_X(0.5-4.5$ keV). If $L_X$ and $T$ are reasonably constant over the Hubble time, a mass $M_{\text{es}} \approx 3 \times 10^{10} M_\odot$ of cold gas is expected to condense from the hot ISM somewhere within NGC 4472. Although this mass is very large, it is only about 4% of the total stellar mass in NGC 4472 today. The mass that cools can therefore be ignored if it is widely distributed throughout the galactic volume. However, the central concentration of Hα emission in ellipticals (e.g., Macchetto et al. 1996) suggests that the cooling is concentrated toward the galactic center where the interstellar density is highest and the bulk of the X-ray energy is emitted.

The motivation of this paper is to explore a variety of options for the mass dropout profile of cooled gas in bright ellipticals appropriately constrained by the known radial distributions of total stellar and nonbaryonic mass. The radial mass dropout profile of cooled gas cannot be determined from first principles because the distribution and amplitude of the entropy and magnetic fluctuations in the hot gas are unknown and difficult to evaluate from simple physical arguments. Nevertheless, the total mass of cooled gas inside an effective (half-light) radius $r_e$ must be consistent with the mass-to-light ratio determined from stellar velocities and with the total mass inferred from X-ray observations within $r_e$. Assuming that the stellar mass-to-light ratio is uniform with radius, the stellar mass $M_e(r)$ and the X-ray mass $M_X(r)$ appear to be in nearly perfect agreement for two bright Virgo ellipticals in the range $0.1 r_e \lesssim r \lesssim r_e$ (Brighenti & Mathews 1997a). Because of constraints on the mass distribution of cooled gas provided by X-ray and stellar dynamical observations, galactic cooling flows provide a critical venue for testing the physics of mass deposition in cooling flows.

The mass of cold ($T \lesssim 10^4$ K) gas $M_{\text{es}}$ actually observed in ellipticals is many orders of magnitude less than the total cooled mass estimated above. For example, neither H I nor H_2 gas has been observed in NGC 4472, only upper limits, $M_{\text{es}} \lesssim 10^7 M_\odot$ (Bregman, Roberts, & Giovanelli 1988; Braine, Henkel, & Wiklind 1997). If stars form, they must either be indistinguishable from the old stellar population or nonluminous. We explore here the possibility that most of the cooled gas forms dense baryonic clouds or stars that are dark at optical and radio frequencies. The very low mass stars advanced by Ferland et al. (1994) satisfy this invisibility criterion, while the star formation models of Mathews & Brighenti (1999) indicate that (luminous) stars of mass $\sim 1-2 M_\odot$ can form in galactic cooling flows.

X-ray studies indicate significant masses of cold, absorbing gas in cluster and galactic cooling flows (e.g., White et al. 1991; Allen et al. 1993; Fabian et al. 1994; Allen & Fabian 1997; Buote 1999), but these results are inconsistent with the absence of radio frequency emission from the cold gas (Braine & Dupraz 1994; Donahue & Vogt 1997) and should be regarded as controversial until this inconsistency is resolved. Even taken at face value, the total mass of cooled gas implied by the X-ray absorption in cluster cooling flows is typically only a small fraction of the total mass that should have cooled in a Hubble time (Allen & Fabian 1997; Wise & Sarazin 1999), implying that most of the cooled gas may have formed stars. If cooled gas forms into small stars, these stars will have apogalactica near their point of origin where they will spend most of their orbital time. We shall assume that the gas mass that cools and drops out of the flow contributes optically dark (stellar) mass at the radius where the cooling occurred.

In the following, we describe a series of gasdynamical calculations for the evolution of X-ray–emitting interstellar gas over the Hubble time and investigate a variety of assumptions about the radial distribution of optically dark cooled gas. To be specific, we compare our models with the well-observed massive elliptical NGC 4472. We find that the mass of cooled gas contributes significantly to dynamical mass-to-light determinations within $r_e$ based on stellar velocities.

2. KNOWN STELLAR AND DARK MASS DISTRIBUTION IN NGC 4472

The E2 elliptical NGC 4472 is a luminous, slowly rotating [$v/\sigma$] = 0.43 galaxy in the Virgo cluster. With an adopted distance $d$ = 17 Mpc, its optical luminosity is $L_B = 7.89 \times 10^{10} L_B\odot$ and its half-light or effective radius $r_e = 1.733$ is 8.57 kpc (Faber et al. 1989). The total stellar mass $M_* = 7.26 \times 10^{11} M_\odot$ is found from the mass-to-light ratio $M/L_B = 9.2$ determined by van der Marel (1991) with a two-integral stellar distribution function. This mass-to-light ratio is appropriate to the galactic region within about 0.4$r_e$ where stellar velocities are well determined, although the mass determined from X-ray observations suggests that $M/L_B$ remains constant to at least $r_e$ (Brighenti & Mathews 1997a). If $M/L_B$ is spatially constant, the stellar mass also has a de Vaucouleurs profile. Within a central core or break radius $r_b = 2.41$ pc, the stellar density profile flattens (Faber et al. 1997), but we shall not consider this small feature here. NGC 4472 contains a central black hole of mass $M_{\text{bh}} = 2.9 \times 10^8 M_\odot$ (Magorrian et al. 1998).

The total mass distribution in luminous ellipticals can most easily be determined from the radial variation of density and temperature in the hot interstellar gas, assuming hydrostatic equilibrium. Figure 1 illustrates the interstellar density and temperature profiles in NGC 4472. The filled circles in Figure 1 are Einstein HRI observations (Trinchieri, Fabbiano, & Canizares 1986) and open circles are ROSAT HRI and PSPC data from Irwin & Sarazin (1996) (also see Forman et al. 1993). The $T(r)$ and $n(r)$ profiles have been fit with analytic curves as described by Brighenti & Mathews (1997a).

Hydrostatic equilibrium in the hot interstellar gas is an excellent approximation since the cooling flow velocity is very subsonic. The total mass interior to radius $r$ deter-
mired from X-ray observations is

\[
M_X(r) = -\frac{kT(r)}{G\mu n_p} \left( \frac{d\log \rho}{d\log r} + \frac{d\log T}{d\log r} + \frac{P_m}{P} \frac{d\log P_m}{d\log r} \right),
\]

where \(n_p\) is the proton mass and \(\mu = 0.61\) is the mean molecular weight. The last term, representing the possibility of magnetic pressure \(P_m = B^2/8\pi\), is negative if \(dP_m/dr < 0\), as seems likely. If the magnetic term is important but not included, the total mass will be underestimated. Assuming \(P_m = 0\), the total mass \(M_X(r)\) in NGC 4472 is shown with a solid line in Figure 1b.

In the outer halo, \(r \gtrsim r_e\), the total mass is dominated by the dark halo. The dark halo mass distribution in NGC 4472 can be approximated with an NFW halo profile (Navarro, Frenk, & White 1996) of virial mass \(M_\text{h} = 4 \times 10^{13} M_\odot\), although the observed halo is somewhat less centrally peaked than NFW (Brighenti & Mathews 1999a). Within \(r_e\), the contribution of the dark NFW halo mass in the model is small; for example, at \(r < r_e/3\) the total mass-to-light ratio is \(M/L_\beta = 10.18\), only 10% greater than the dynamic value 9.2 determined in \(r \lesssim 0.4r_e\).

It is remarkable that the total mass found from the X-ray data \(M_X(r)\) is nearly identical to the expected dynamical mass \(M_{\odot}(r)\) (based on stellar velocities and \(M/L\)) in the range \(0.1r_e \lesssim r \lesssim r_e\) (Fig. 1). An almost identical agreement in this radius range is indicated by X-ray observations of another bright Virgo elliptical, NGC 4649 (Brighenti & Mathews 1997a). In this important region, the hot gas is confined by the stellar potential. The excellent agreement of the stellar and X-ray masses supports the consistency of two radically different mass determinations: from stellar velocities and from the radial equilibrium of hot interstellar gas. The apparent agreement of the X-ray and stellar masses in this range of galactic radii also indicates that the hydrostatic support of the hot gas is not strongly influenced by local magnetic fields and rotation.

However, it is not obvious why \(M/L_\beta\) would be constant with galactic radius, particularly when the cooling dropout mass is considered, and why the agreement between stellar
dynamic and X-ray masses no longer obtains in the central regions \(r \lesssim 0.1r_e\). In this central region, the total mass indicated by the X-ray observations in Figure 1 is considerably less than the expected mass based on an assumed de Vaucouleurs profile and constant mass-to-light ratio. This type of deviation could be due to magnetic or other nonthermal pressure in this region, to rotation, or to local cooling dropout in the hot interstellar gas. The lower mean temperature in cooling regions lowers the total apparent gas temperature and results in an underestimate of the total internal mass (eq. [1]).

We assume that currently available Einstein and ROSAT observations are accurate in the central region of NGC 4472, \(r \leq 0.1r_e\). These observations have been reduced assuming no (non-Galactic) photoelectric absorption by low-temperature gas in the central regions. If X-ray absorption is present, the true hot gas density would be more centrally peaked than shown in Figure 1 and the total mass indicated by the X-ray observations would increase. Buote (1999) finds that two-temperature models fit the X-ray spectrum for NGC 4472 quite well. The two temperatures do not necessarily need to be spatially mixed; they could also approximately represent the range of the radial temperature variation observed in NGC 4472. In Buote’s two-temperature model, only the cooler component \((T \approx 0.7\) keV located in \(r \leq r_e\)) requires an absorption column \(N_H = 2.9 \times 10^{21} \text{ cm}^{-2}\) in excess of the Galactic value. Moreover, the influence of cold gas having this column density on the hot gas density plotted in Figure 1 is small. For a worst case example, suppose that absorbing material with column density \(N_H = 2.9 \times 10^{21} \text{ cm}^{-2}\) is in a disk oriented perpendicular to the line of sight and that this disk absorbs all X-rays from the back side of the galaxy. The radius of this disk would be less than 370 pc if it contained the maximum mass \(M_\odot \sim 10^7 M_\odot\) allowed by CO and H I observations (Bregman et al. 1988; Braine et al. 1997) or 20 kpc if it contained all of the gas that has cooled, \(M_\odot = 3 \times 10^{10} M_\odot\). The X-ray surface brightness within the opaque disk would be reduced by 2, but the corresponding gas density would be lowered by only \(2^{1/2} \times 10^{0.13}\) since the volume emissivity \(\propto n^2\). Such a small correction in the density (gradient) could not account for the large mass discrepancy between the X-ray mass and the stellar dynamical mass shown in Figure 1 within \(0.1r_e\).

The densities and temperatures in Figure 1 were determined from X-ray data assuming the abundance of the hot gas is uniformly solar. Since the gas is likely to be more metal-rich at smaller galactic radii (Matsushita 1997; Brighenti & Mathews 1999b), an allowance for this gradient would tend to lower the derived density gradient and the internal mass, increasing the discrepancy in \(r \leq 0.1r_e\) in Figure 1 by a small amount. In the following discussion, we shall ignore the relatively small possible influence of absorption or metallicity gradients on the results shown in Figure 1.

3. HYDRODYNAMICAL MODELS

The hydrodynamical models we use in this paper are similar to those in our recent papers (e.g., Brighenti & Mathews 1999a), so we provide only a brief review here. Hot interstellar gas in ellipticals has a dual origin: (1) mass loss from an evolving old stellar population and (2) secondary inflow in the overdensity perturbation that formed the galaxy group within which the elliptical formed by early
merging events. For a given set of cosmological parameters, dark and baryonic matter flow toward an overdensity region. The dark matter forms an NFW halo, growing in size with time. Spherical geometry is assumed. Within the accretion shock at time $t_\star = 2$ Gyr, when enough baryons have accumulated, we form the current de Vaucouleurs stellar profile and release the energy of all Type II supernovae according to a Salpeter initial mass function (IMF) (slope: $\xi = 1.35$; mass limits: $m_1 = 0.08$ and $m_\infty = 100$ $M_\odot$). All stars larger than $8$ $M_\odot$ produce Type II supernovae each of energy $E_{SN} = 10^{51}$ ergs. We assume that a fraction $\epsilon_{SN} = 0.8$ of this energy is delivered to the internal energy of the gas. We have shown (Brighenti & Mathews 1999b) that such a galaxy formation scheme can work in a variety of cosmologies: flat or low density, with or without a lambda term. The evolution of gas within the optical effective radius $r_\star$, of most interest here, is insensitive to these cosmological parameters. For simplicity, therefore, we assume a simple flat universe with $\Omega = 1$, $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$, and $\Omega_\Lambda = 0.05$. We characterize the dark halo with an NFW profile (Navarro et al. 1996) having a virial mass $M_v = 4 \times 10^{13}$ $M_\odot$ at the current time $t_\star = 13$ Gyr. The models we discuss here are identical to the standard model of Brighenti & Mathews (1999a) except we now use a finer central spatial zoning ($65$ pc for the innermost zone), a SN II efficiency $\epsilon_{SN} = 0.8$, and a mass “dropout” function $q(r)$ with more adjustable parameters (see below).

Our objective is to seek solutions of the gasdynamical equations including mass dropout that jointly satisfy several observational constraints at time $t_\star$: (1) the observed hot gas density, temperature, and X-ray surface brightness profiles; (2) the known dynamical mass in the galactic center usually attributed to a massive black hole; (3) the apparent dynamical mass-to-light ratio $M/L_B = 9.2$ determined in $r \leq 0.4r_\star$; and (4) an apparent internal mass $M_x(r)$ in $(0.1-1)r_\star$ based on equation (1) that agrees with the constant $(M/L_B)$ de Vaucouleurs profile as shown in Figure 1.

The baryonic component in our models has a complex evolution. Much of the initial baryonic mass is consumed in creating the stellar system. When the Type II supernova energy is released, a significant mass of gas is expelled as a galactic wind. After these early events, the interstellar gas is reestablished and sustained by stellar mass loss and by inflow of circumgalactic gas (secondary infall), most of which was previously enriched and expelled by SN II. We assume that the stars form during a short epoch that can be described by a single-burst Salpeter IMF as discussed above. The stellar mass-loss rate for this IMF varies as $M_{st} = \alpha(t)M_{st0}$, where $\alpha(t) = 4.7 \times 10^{-20}[t/(t_\star - t_{st0})]^{-1.3}$ s$^{-1}$. Although galactic stars form at $t_{st0} = 1$ Gyr, their mass-loss contribution to the ambient interstellar gas is assumed to begin at a later time, $t_{st} = 2$ Gyr. Since galactic stars have been enriched by supernova ejecta, the single-burst model cannot be strictly correct, but our approximation $\alpha(t < t_{st}) = 0$ is consistent with several early starbursts closely spaced in time and allows for metal enrichment of old galactic stars that are not in the first single-burst population. If the de Vaucouleurs profile is a result of largely dissipipationless merging, some or most of the star formation must have occurred at a time $t_{st}$ before the important merging events at $t_\star = 2$ Gyr. By taking $t_{st} < t_{st}$, we reduce by $\sim 10^{10}$ $M_\odot$ the total amount of gas ejected by stars within the galactic potential. We recognize the inconsistencies in these approximations of complex stellar formation and dynamical processes that are poorly understood. However, once the galaxy is formed, we follow the interstellar gas dynamical evolution in full detail, conserving mass and energy.

Continued heating by Type Ia supernovae is assumed to vary inversely with time, $SN_{Ia}(t) = SN_{Ia}(t_\star/t_\star)$, where the current rate, $SN_{Ia}(t_\star) = 0.03$ SN 1a per 100 yr per $10^{10}$ $L_B$, is near the lower limit of observed values, $SN_{Ia}(t_\star) = 0.06$ $\pm 0.03(H/50)^2$ (Cappellaro et al. 1997), as required to maintain the low interstellar iron abundance.

For the models discussed here, the equation of continuity includes a “mass dropout” term:

$$\frac{\partial \rho}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r}(r^2 \rho u) = \alpha \rho_* - q(r) \rho_{do},$$

where $t_{do} = 5m_{p}kT/2\mu\Lambda$ is the time for gas to cool locally by radiative losses at constant pressure (see, e.g., Sarazin & Aske 1989). The cooling is assumed to be instantaneous without advection in the cooling flow, i.e., $t_{do} \ll t_{flow} = r_{flow}/v$, although in practice this inequality may not always be satisfied. While this type of cooling dropout has been widely used in past models, there is no adequate physical model for mass dropout. Clearly, the gas must cool somewhere—the emission of X-rays indicates a large net energy (and mass) loss from the interstellar medium.

When small regions of low entropy cool, the pressure remains constant since the sound crossing time is much less than the flow time. Following Fabian et al. (1982) and Ferland et al. (1994), we assume that cooled gas converts to a second population of optically dark, low-mass stars. Regarding H\alpha emission as a tracer for the cooling gas, Mathews & Brighenti (1999) have shown that the cooling occurs at a multitude ($10^4$) of cooling sites distributed throughout the inner galaxy and that only stars with mass $\lesssim 1-2$ $M_\odot$ can form at each cooling site. This is supported by the observed absence of young massive stars and SN II in elliptical galaxies. Nevertheless, in the following discussion we assume that the maximum stellar mass in the dropout population is sufficiently low that the optical light from these stars is unobservable. We expect cooling and low-mass star formation to be concentrated within at least $2$ kpc, which is the observed extent of H\alpha emission in NGC 4472 (Macchetto et al. 1996). While the region containing optical emission lines provides a natural guideline for selecting the dropout profile, we consider a wider range of constant or variable dropout coefficients $q(r)$ parameterized by

$$q(r) = q_0 \exp \left(\frac{-r}{r_{do}}\right)^m,$$

which concentrates the cooling within radius $r_{do}$. Note that even when $q$ is constant the mass dropout term is spatially concentrated, $\rho/t_{do} \propto r^2$.

### 4. MODELS WITH ZERO OR CONSTANT $q$

In a series of recent papers in this journal, we have presented evolutionary cooling flow models for NGC 4472 that agree quite well with the observed distributions of interstellar gas density, temperature, and metallicity (Brighenti & Mathews 1999a; 1999b), particularly at intermediate and large radii. Since the total mass of cooled gas in these calculations was only a few percent of the stellar mass, the gravitational contribution of cooled gas was ignored, even in models including mass dropout. For a better understanding of the inner galaxy, we now include the gravity of all gas,
both hot and cold, except when specifically noted. In this section, we begin with models having $q = 0$ everywhere, so that cooling to low temperatures occurs in a small central region, then we investigate models in which $q$ is constant throughout the cooling flow.

**4.1. Models without Distributed Mass Dropout ($q = 0$)**

We begin by considering a perfectly homogeneous interstellar flow in which all the gas reaches the central computational zone ($r = 65$ pc) or its neighboring zones, where it then cools to $T \ll 10^7$ K. For comparison we discuss two cases: in model 1 we ignore the gravity of this cooled gas and in model 2 (and subsequent models) we include its gravitational influence on the flow. The mass of gas that cools into the central grid zone is dynamically equivalent to a massive black hole, but we do not necessarily regard our calculation as a realistic model for black hole formation. In Figure 2a, we illustrate the radial variation of gas density and temperature for models 1 and 2 after the interstellar gas has evolved to $t = t_1 = 13$ Gyr. Several global parameters for these and subsequent models are listed in Table 1.

When the gravity of the cooled gas is considered (model 2), the interstellar gas within a few kiloparsecs of the galactic center is compressed and sharply heated in the local potential. Such hot central thermal cores are not generally observed (but see Colbert & Mushotzky 1999). The central mass in both models, $M_{\text{cen}} \approx 4.65 \times 10^{10} M_\odot$ is about 16 times larger than the black hole mass found in NGC 4472, $M_{\text{bh}} = 2.9 \times 10^9 M_\odot$ (Magorrian et al. 1998). For these reasons, neither model 1 nor 2 provides a realistic interstellar mass distribution for this galaxy.

**ROSAT**-band X-ray surface brightness profiles $\Sigma_X(r)$ for models 1 and 2 are shown in Figure 2b, and the total ROSAT-band luminosities are listed in Table 1. For model 1, the X-ray brightness peaks strongly in the galactic center, diverging from the observations within about 3 kpc; it was just this sort of disagreement that initially led to the assumption of distributed mass dropout in cooling flows (Thomas 1986; Vedder et al. 1988; Sarazin & Ashe 1989). If the efficiency of heating by early SN II were lowered, models 1 and 2 could be made to agree better with $\Sigma_X$ observations in $r \gtrsim 10$ kpc, but the computed $\Sigma_X$ would rise even further above the observations within a few kiloparsecs. The X-ray luminosities $L_X$ for models 1 and 2 listed in Table 1 are unreliable in part because of numerical inaccuracies caused by the extremely steep variation of gas temperature and density in the central two or three computational zones. This numerical difficulty is common to all cooling flows that proceed to the very center of the galaxy before cooling, for any reasonable central grid spacing. Since more $P dv$ work is done on the flow in model 2 (where the gravity of cooled gas is included), we expect that $L_X$ should also be larger than for model 1. The opposite sense of the change in $L_X$ shown in Table 1 evidently results from numerical inaccuracies near the central singularity where zone-to-zone variations are no longer linear. If the gas has not cooled before flowing into the core ($\lesssim 100$ pc), as in models 1 and 2, a significant fraction of the total X-ray emission should come from this very central region, again in disagreement with observations.

In models 1 and 2, a sphere of cold ($T = 10$ K) dense gas accumulates in the central grid zones and grows in mass and size over the Hubble time. This sphere is an unrealistic artifact of our computational assumptions. Therefore, to explore further the central numerical difficulty with $L_X$ encountered in models 1 and 2, we considered two additional models using higher spatial resolution (radius of central zone is only 15 pc), both of which include the gravitational influence of cooled gas. The first model (model 2.1) is similar to model 2 with $q = 0$ in all zones. In the second model (model 2.2), we set $q = 0$ in all zones except the central zone, where $q = 4$. Model 2.2 is the appropriate limit of the series of models discussed below in which the cooling dropout is more and more centrally concentrated.

While the flow in $r \gtrsim 1$ kpc is very similar in models 2.1 and 2.2, the behavior at smaller radii is quite different. For example, the flow parameters for model 2.1 at 100 pc and $t_2 = 13$ Gyr are $T = 7.9 \times 10^7$ K, $n = 1$ cm$^{-3}$, and $u = -320$ km s$^{-1}$. At the same radius and time for model 2.2, the flow variables are $T = 6.3 \times 10^7$ K, $n = 5$ cm$^{-3}$, and $u = -60$ km s$^{-1}$. At projected radius $R = 100$ pc, the ROSAT X-ray surface brightness in model 2.2 is 20 times larger than model 2.1 and the total ROSAT X-ray luminosity integrated over the entire cooling flow in model 2.2 is larger by a factor of 32. The differences between these two models result from upstream propagation of information about the central boundary conditions made possible by subsonic flow near the origin. Fortunately, these numerical and physical difficulties near the origin do not arise in more realistic cooling flows discussed below in which $q > 0$ at larger galactic radii.

**4.2. True and Apparent Gas Density and Temperature**

While solutions of the gasodynamical equations provide the temperature as a function of physical radius $T(r)$, the observed temperature $T(R)$ is an emission-weighted mean temperature along the line of sight at projected radius $R$. For symmetric galaxies and at small galactic radii, these two temperatures are nearly identical because of the steep radial variation in X-ray emissivity. The variation of temperature with physical radius $T(r, t)$ in the background flow is shown with light solid lines in Figure 2a.

In the presence of spatially distributed cooling dropout, the local temperature is an emission-weighted mean of the background (uncooled) gas and the cooling regions. Cooling is assumed to occur at a large number of cooling sites where the gas remains in pressure equilibrium as it cools, apparently unrestricted by magnetic stresses (see Mathews & Brighenti 1999 for details). The heavy solid lines in Figure 2a show the mean apparent temperature $T_{\text{eff}}(r, t)$ including contributions from locally cooling regions,

$$T_{\text{eff}} = \frac{T + qT\Delta_4(T)}{1 + q\Delta_6(T)},$$  \hspace{1cm} (3)

where $T$ is the background flow temperature and the slowly varying functions $\Delta_4(T)$ are plotted in Brighenti & Mathews (1998). Note that the effective temperature is independent of the local gas density. The temperature that is actually observed is an average of $T_{\text{eff}}$ along the line of sight; this temperature $T_{\text{eff}}(R, t_2)$ is shown with dotted lines in Figure 2a.

Similarly, the apparent hot gas density is increased because of additional emission from denser, cooling-out gas. The observed electron density shown in Figure 2a is found by Abel inversion of the X-ray surface brightness distribution. When cooling sites are present, the local
Fig. 2.—(a) Comparison of observed hot gas density and temperature in NGC 4472 with various hydrodynamical models at time $t_n = 13$ Gyr. The source of observed data in all panels is identical to that in Fig. 1. *Light solid lines:* Density and temperature of the background flow as functions of physical radius $r$. *Heavy solid lines:* Apparent density and temperature as functions of $r$ including emission from cooling regions. *Dotted lines:* Apparent gas temperature as a function of projected radius, similar to the temperature data points. (b) Comparison of ROSAT and Einstein X-ray surface brightness distributions in NGC 4472 with various models. *Light solid lines:* Emission just from the background cooling flow. *Heavy solid lines:* Combined emission from background and distributed cooling regions.
TABLE 1
MASS DROPOUT MODELS FOR NGC 4472

| Model | \(q_0\) | \(r_{do}\) (kpc) | \(m\) | \(M_\text{es}\) \(\times 10^{10} M_\odot\) | \(M_\text{es}(r_{r/3})\) \(\times 10^{11} M_\odot\) | \(M_\text{g}(r_{r/3})\) \(\times 10^{11} M_\odot\) | \(M_\text{g}/L_\text{B}(r_{r/3})\) | \(\Delta_\text{g}(r_{r/3})\) | \(M_\text{cent}\) \(\times 10^{10} M_\odot\) | \(L_{\text{X,bck}}\) \(\times 10^{40}\) erg s\(^{-1}\) | \(L_{\text{X,tot}}\) \(\times 10^{40}\) ergs s\(^{-1}\) |
|-------|-------|-----------------|-----|----------------|-----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 1      | 0     | ...             | ... | 4.64           | 4.64            | 1.35\(i\)      | 1.36           | 13.70          | 0.00           | 4.64           | 28.6           | 28.6           |
| 2      | 0     | ...             | ... | 4.66           | 4.66            | 1.81           | 1.70           | 13.71          | 0.34           | 4.66           | 21.7           | 21.7           |
| 3      | 1     | ...             | ... | 36.1\(b\)      | 2.64            | 1.61           | 1.26           | 12.19          | 0.19           | 0.254          | 18.7           | 36.4           |
| 4      | 4     | ...             | ... | 81.1\(l\)      | 1.36            | 1.48           | 0.97           | 11.21          | 0.10           | 0.013          | 8.8            | 42.6           |
| 5      | 4     | 15              | 1   | 4.65           | 1.55            | 1.50           | 1.01           | 11.36          | 0.11           | 0.013          | 13.9           | 27.7           |
| 6      | 4     | 2               | 1   | 4.65           | 3.76            | 1.72           | 1.51           | 13.03          | 0.27           | 0.015          | 22.1           | 33.5           |
| 7      | 4     | 0.8             | 2   | 4.65           | 4.65            | 1.81           | 1.76           | 13.71          | 0.34           | 0.017          | 29.1           | 43.3           |
| 8\(\text{a}\) | 4   | 2               | 1   | 4.60           | 3.65            | 1.29           | 1.17           | 9.74           | 0.40           | 0.012          | 20.0           | 28.1           |

\(\text{Note.}\) All masses evaluated at time \(t_e = 13\) Gyr.

a Total cooled mass within 1 Mpc.
b Mass of cooled gas within \(r_{r/3} = 2.86\) kpc.
c Total mass within \(r_{r/3} / M_\text{es}(r_{r/3}) = 1.36 \times 10^{11} M_\odot\).
d Mass of cooled gas at \(r_{r/3}\) evaluated using hydrostatic equilibrium.
e Ratio \(M_\text{es}(r_{r/3}) / L_\text{g} = 10.18\) is the value for the stars and dark halo for models 1–7.
f Relative contribution of dropout mass to \(M/L_B\) at \(r_{r/3}\).
g Mass cooled into central grid zone; the central black hole in NGC 4472 has mass \(M_{bh} = 0.29 \times 10^{10} M_\odot\).
h \(ROSAT\) X-ray luminosity (0.2–2 keV) of background flow.
i Total \(ROSAT\) X-ray luminosity including emission from dropout.
j Mass of cooled gas is not included.
k Mass within 100 kpc is \(4.72 \times 10^{10} M_\odot\).
l Mass within 100 kpc is \(4.96 \times 10^{10} M_\odot\).
m With lower \(M/L_B\) for old stars.
emissivity into the ROSAT energy band is
\[ \varepsilon_{AE} = (\rho/\sqrt{m_p})^2 \Lambda_{BE}(T) \]
\[ = (\rho/\sqrt{m_p})^2 \Lambda_{BE}(T)[1 + \Delta_0(T)] \text{ ergs s}^{-1} \text{ cm}^3 . \]
The effective density is therefore
\[ n_{\text{eff}} = n[1 + \Delta_0(T)]^{1/2}, \quad (4) \]
where \( n \) is the electron density of the background, uncooled gas. The observed (azimuthally averaged) densities in NGC 4472 plotted in Figure 2a should be compared with \( n_{\text{eff}}(r, t_B) \), shown with heavy solid lines.

4.3. Distributed Mass Dropout with Constant \( q \)

Lacking an acceptable physical model for spatially distributed mass dropout in galactic cooling flows, we are at liberty to choose any variation for the dropout coefficient \( q(r) \), appropriately constrained a posteriori by the known dynamical mass from stellar velocities, the X-ray mass, the central black hole mass, and the observed radial variation of hot gas density, temperature, and X-ray surface brightness. It is natural to begin with constant \( q \) solutions similar to those considered by Sarazin & Ashe (1989) in their steady state cooling flow solutions. For simplicity, we assume that the mass of cooled gas remains at the cooling site where it contributes to the gravitational potential.

In the central panels of Figure 2a, we illustrate the hot interstellar gas density and temperature that results after \( t_B = 13 \text{ Gyr} \) assuming uniform \( q = 1 \) and 4; these are listed in Table 1 as models 3 and 4, respectively. When \( q \) is a constant independent of radius, the ratios of true to apparent values—\( n/n_{\text{eff}} \), \( T/T_{\text{eff}} \), and \( M_{\text{tot}}/M_X \)—are also approximately uniform with galactic radius. Here \( M_{\text{tot}}(r) \) is the true total mass within \( r \), and \( M_X(r) \) is the value that would be determined from X-ray observations of the models by assuming hydrostatic equilibrium (as in Fig. 1). The influence of constant \( q \) mass dropout is similar at all galactic radii since the factors that convert background temperature and density to effective values in equations (3) and (4) depend only on \( T(r) \), which is slowly varying, not on \( n(r) \).

Because of the enormous volume and time available to gas dropping out at large \( r \), the total mass of cooled gas (listed in Table 1) becomes very large in the outer galaxy. In Figure 3, we compare the radial distribution of stellar and dark halo mass with the distributed dropout mass that results after 13 Gyr with \( q = 1 \) and 4. The de Vaucouleurs “stellar” mass profile in Figure 3 is constructed assuming uniform \( M/L_B = 9.2 \).

As \( q \) increases from 1 to 4, the background hot gas density (Fig. 2a, light solid lines) decreases and its radial gradient flattens, causing a rise in temperature to provide enough pressure to support the cooling flow atmosphere. Note that the total dropped out mass within \( r_c/3 \) decreases with larger \( q \) (Fig. 3 and Table 1). Although more overall cooling dropout occurs as \( q \) increases, most of this cooling occurs at very large \( r \) and, somewhat paradoxically, less gas remains for dropout closer to the galactic center, \( r \lesssim r_c \).

However, the effective (i.e., apparent) density (Fig. 2a, heavy solid lines) is less sensitive to \( q \). The \( q = 1 \) solution (model 3) is preferred for its fit to observed temperatures while the \( q = 4 \) solution (model 4) agrees better with the observed density in \( r \lesssim 10 \text{ kpc} \) and almost exactly with the X-ray surface brightness (Fig. 2b).

In addition, the centrally concentrated dropped out mass in the \( q = 1 \) solution (model 3) contributes a larger fraction of the dynamical mass in \( r \lesssim r_c/3 \), and the total mass within the central grid zone (\( r = 65 \text{ pc} \)) is almost equal to the known mass of the black hole in NGC 4472 (Table 1). Evidently, cooled masses in models with \( q < 1 \) would exceed the central dark mass observed.

For both values of \( q \) considered, the dropped out mass listed in Table 1 contributes appreciably to the total mass within \( r = r_c/3 \). When both old stellar and dropout mass are included, the \( M/L_B \) values at \( r_c/3 \) shown in Table 1 (12.19 and 11.21) exceed both the dynamical value \( M/L_B = 9.2 \) found by van der Marel (1991) within \( \sim 0.4r_c \) and the value \( M/L_B(r_c/3) = 10.18 \) in our models which includes a small additional contribution of nonbaryonic dark matter. To quantify the influence of the dark baryonic dropout mass on the mass-to-light ratio, we include in Table 1 an entry for
\[ \Delta_{m_1}(r_c/3) = \frac{M(r_c/3) - M_1(r_c/3)}{M_1(r_c/3)} \]
where \( M_1(r_c/3) = 1.35 \times 10^{11} M_\odot \) is the combined mass of luminous stars and dark halo matter at \( r_c/3 \) and \( M_1(r_c/3) \) also includes the dropout mass within this radius. Since our computed total mass \( M_1(r_c/3) \) exceeds the observed dynamical value 9.2 (and also 10.18), to be fully consistent we should have chosen \( M/L_B < 9.2 \) for the old stellar population (see below), provided \( M/L_B \) for stars produced from the cooled gas is infinite as we have assumed.

If these constant \( q \) models are physically appropriate, the agreement between \( M_X(r) \) and \( M_1(r) \) in (0.1–1)\( r_c \), as shown

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**Fig. 3**—Baryonic and nonbaryonic mass distributions in NGC 4472. Light solid line: De Vaucouleurs profile of dynamical mass based on \( M/L_B = 9.2 \). Heavy solid line: NFW dark halo profile for best fit to NGC 4472 data. Short-dashed line: Cooled dropout mass \( M_{\text{cd}} \) for model 1. Long-dashed line: Cooled dropout mass \( M_{\text{cd}} \) for model 4. Dotted line: Cooled dropout mass \( M_{\text{cd}} \) for model 6. Short dash-dotted line: Cooled dropout mass \( M_{\text{cd}} \) for model 7. Long dash-dotted line: Cooled dropout mass \( M_{\text{cd}} \) for model 8.
in Figure 1 (and for NGC 4649), is surprising since \( M_X(r_3/3) \) and \( M_{\ast, d}(r_3/3) \) differ by 10\%-40\% (Table 1) for the constant \( q \) models. This suggests that the mass-to-light ratio of the dropout stellar population is not infinite as we have assumed but comparable to that of the old stellar population.

5. MODELS WITH CENTRALLY CONCENTRATED DROPOUT

We now seek evolutionary gasdynamical solutions with variable dropout coefficients \( q(r) \) that strongly concentrate the mass dropout in the inner galaxy, \( r \lesssim r_c \). The limited spatial extent of optical emission lines in the cores of bright ellipticals suggests that most cooling dropout occurs well within \( r_c \). For example, the H\(\alpha \) [N\(\text{ii} \)] image of NGC 4472 is observed out to \( \sim 0.25r_c \) or 2 kpc (Macchetto et al. 1996). As hot interstellar gas cools in this region, its temperature decreases at \( T \sim 10^6 \) K where the gas is heated and ionized by stellar UV radiation. Therefore, we consider parameters \( r_{do} \) and \( m \) in equation (2) that concentrate the mass dropout in the central region but not at the very center as in model 2.

The dropout parameters \( r_{do} \), \( r_{do} \), and \( m \) are listed in Table 1 for models 5, 6, and 7. The mass dropout in these three models is progressively more concentrated toward the galactic center. The results for model 5, for which the dropout scale length is very large, \( r_{do} = 15 \) kpc, are similar in most respects to those of model 4 except the massive dropout in the outer galaxy is no longer present. In particular, the mass-to-light ratio at \( r_3/3 \) in Table 1 is very similar for models 4 and 5.

The current interstellar density and temperature variations for model 6 with \( r_{do} = 2 \) kpc are shown in Figure 2a, and \( \Sigma_X(R) \) is plotted in Figure 2b. The apparent density and \( \Sigma_X \) (heavy solid lines) are considerably greater than observed values in \( r \lesssim 3 \) kpc, although the projected apparent temperature is a reasonable fit to the NGC 4472 data. The radial distribution of dropout mass for model 6 is shown in Figure 3. From Table 1, the total (old stars, halo, and dropout) mass-to-light ratio at \( r_3/3 \) is \( M_{do}/L_B = 13.03 \), 29\% higher than van der Marel’s value and 22\% greater than the corresponding value for our background model galaxy.

Also shown in Figures 2a and 2b are similar results for model 7 in which the mass dropout, now approximated with a Gaussian, is concentrated within \( r_{do} = 800 \) pc. Model 7 is constructed so that most of the mass dropout occurs in \( r \lesssim 0.1r_e \), corresponding to the region of apparent disagreement between \( M_X \) and \( M_\ast \) in Figure 1. It is of interest that the gas density and \( \Sigma_X \) within 1 kpc for model 7, where the dropout is greatest, exceeds those of model 2, in which there is no dropout at all. This can be understood from the flow velocity distribution. For model 2 without distributed dropout, the inward moving gas velocity increases through the entire region illustrated and shocks at \( r \lesssim 1 \) kpc. In the presence of dropout, the flow velocity at corresponding radii in model 7 is much slower and reaches a maximum (negative) value near \( r = 1 \) kpc then approaches zero subsonically at the origin. The density and \( \Sigma_X \) enhancements in the background flow for model 7 at \( r \lesssim 3 \) kpc are due to a local compression as the gas flows into slowly moving gas in the core. Within about 3 kpc, both the background and apparent densities exceed the observations by a larger factor than those of model 6 and \( \Sigma_X \) also peaks unrealistically in this same region (Fig. 2b). The dropout mass for model 7 shown in Figure 3 equals that of the old population stellar mass at \( r \approx 1 \) kpc (0.12\(r_e\)). For these reasons, model 7 seems less satisfactory than model 6, but neither is as generally successful as model 3 (\( q = 1 \)).

Although increased mass dropout can decrease the X-ray surface brightness \( \Sigma_X \), as when uniform \( q \) increased from 1 to 4 (models 3 and 4 in Fig. 2b), this is not always the case. When the dropout is concentrated more toward the galactic center, \( \Sigma_X \) actually increases, as in the transition from model 6 to 7.

It is interesting to determine the influence of distributed dropout on the total apparent mass \( M_X(r) \) found from the model by assuming hydrostatic equilibrium (eq. [1]). Due to the contribution of low-temperature cooling regions to the total X-ray emission, \( T(r) \) and therefore \( M_X(r) \) is always lower than the true mass \( M_{\ast, d}(r) \) in cooling dropout regions. A difference in this sense is apparent in Table 1 at \( r = r_3/3 \) for models 3–7; this is similar to the mass discrepancy in Figure 1 at \( r \lesssim 0.1r_e \).

The high central apparent gas density and surface brightness for model 6 shown in Figures 2a and 2b are obvious problems for this model. However, the gas density can be reduced if a strong magnetic field or other nonthermal energy density is present in \( r \lesssim 0.25r_c = 2 \) kpc. Dynamically important magnetic fields may also be required to fit the X-ray data of NGC 4636 (Brighenti & Mathews 1997a) and may be generally expected in luminous ellipticals (Mathews & Brighenti 1997; Godon, Soker, & White 1998). Additional nonthermal pressure support is also implied for model 6 since the effect of central cooling dropout fails to lower the apparent mass \( M_X(r) \) below the actual mass \( M_{\ast, dt} \) as much as the observed deviation shown in Figure 1. Like many bright ellipticals, NGC 4472 has a weak nonthermal radio source within the central ~4 kpc, indicating \( B \sim 10–100 \mu G \) (Ekers & Kolany 1978).

For all calculated models in Table 1 with distributed dropout, the total mass \( M_{\ast, dt} = M_{\ast, dh},d,do \) significantly exceeds the mass of the old stellar population plus dark halo \( M_{\ast, dh} \) throughout the inner galaxy, indicating that dropout material makes an important additional contribution to the total mass. However, the apparent mass \( M_X \) determined from equation (1) is less than \( M_{\ast, dt} \) in the inner galaxy and, for model 6, can also be less than \( M_\ast \). Of particular interest is the region \( 0.1r_e \lesssim r \lesssim r_c \) (i.e., \(-0.07 \lesssim \log r_{pc} \lesssim 0.93 \)) in Figure 1. Although the agreement in Figure 1 is excellent in this region, for models 6 and 7 the total mass is larger than \( M_{\ast, dt} \) and values of \( \Delta_{M_{\ast}} \) in Table 1 suggest that the dropped out mass contributes 25\%-35\% of the total mass in this region. Therefore, if the dropout mass is optically dark, the true stellar mass-to-light ratio of the old stellar population must be \( M/L_B \approx 6 \) rather than the value \( M/L_B = 9.2 \) found by van der Marel which includes the dropout mass.

To investigate such a possibly more self-consistent old stellar component, we consider model 8 based on the same \( q(r) \) used in model 6 but with \( M/L_B = 6 \) for the old stellar population. For additional consistency in model 8, \( \sigma_\ast(r) \) is increased by the ratio of assumed stellar mass-to-light ratios \( 9.2/6 = 1.53 \) as described below; the total stellar mass ejected is identical to that in model 6. Figure 3 illustrates the dropout mass profile for model 8. The apparent density, temperature, and \( \Sigma_X \) profiles for model 8 shown in Figures 4a and 4b are very similar to those of model 6, so this adjustment of the stellar \( M/L_B \) has had little effect.

The radial mass profiles of models 6 and 8 are compared in Figure 5. In this plot, the open circles show the observed
X-ray mass $M_X(r)$ for NGC 4472 using equation (1) and the solid lines show $M_X(r)$ based on equation (1) using $n(r)$ and $T(r)$ from the models. The dashed lines show $M_{\text{tot}}(r)$ and the dotted lines are the stellar mass $M_*(r)$ based on a de Vaucouleurs profile with $M/L_B = 9.2$ in the upper panel (model 6) and $M/L_B = 6$ in the lower panel (model 8). The superiority of model 8 is evident from the closer agreement between the X-ray mass data points for NGC 4472 and the solid line for that model. This agreement for model 8 would be even closer in the range $\log r \approx 0.5$–1 if we had used a dark halo mass profile less centrally peaked than NFW. Model 8 may provide the most self-consistent overall fit to the mass constraints for NGC 4472; if so, the old stars in NGC 4472 have a mass-to-light ratio $M/L_B \approx 6$, ~30% lower than the mass-to-light ratio determined from stellar dynamics.

In summary, none of our models is fully satisfactory in every respect. The total mass-to-light ratio (including dropout mass) in $r \leq r_e/3$ is 10%–35% higher than the value for the underlying galaxy. However, in model 8 in which $M/L_B = 6$ for the old stars, the difference between the X-ray...
mass determined from the models and NGC 4472 is appreciably reduced. Nevertheless, the central apparent gas density and X-ray surface brightness in model 8 are still larger than observed, requiring additional nonthermal support. There is no independent theoretical justification for the dropout profile \( q(r) \) assumed in models 6 and 8; as explained earlier, the dropout distribution depends on unknown interstellar entropy fluctuations. Nevertheless, for all models considered here the mass of cooled interstellar gas contributes significantly to the total mass and the dynamically determined mass-to-light ratio within the inner galaxy.

6. FINAL REMARKS AND CONCLUSIONS

In this series of calculations, we have taken a census of all baryons involved in the evolution of a large elliptical galaxy: the original stellar component, the interstellar medium, and—of most interest—the small but troublesome mass of hot gas that cools over cosmic time. We have shown that the radial distribution of cooled interstellar gas influences dynamical and X-ray determinations of the total interior mass and the radial profiles of apparent density, temperature, and X-ray brightness of the hot gas. In our models, cooled gas is slowly deposited in the central galaxy \( r \lesssim r_c \) (see Fig. 3), as indicated by the extent of observed H\(_{\alpha} \) emission. Since there is little or no direct observational evidence for the mass that has dropped out in ellipticals like NGC 4472, the cooled mass must either be dark at optical and radio frequencies or indistinguishable from the old stars. Low-mass stars are an obvious and physically reasonable end state for the cooled gas (Ferland et al. 1994; Mathews & Brighenti 1999). We also suppose that the cooled gas remains at the dropout site, where it contributes to the galactic potential.

6.1. Reducing Stellar Mass Loss

In an attempt to reduce the influence of cooling and cooled gas on the models, we have altered many of the model parameters. The chosen cosmology (\( \Omega = 1; \Omega = 0.3, \) and \( \Omega = 0.7, \) etc.) or the baryon fraction \( \Omega_b \) have little influence on the total dropout mass. Changing the times when the stars and the galactic potential form \( (t_s, t_e) \) or the spatial scale of the release of SN II energy within reasonable limits have only a modest influence on the dropout mass that accumulates by time \( t_e = 13 \) Gyr. Increasing the interval \( t_{se} - t_s \) between star and galaxy formation does reduce the total dropout mass, but this interval cannot be too large since luminous ellipticals are observed at large redshifts. The cooling dropout would not be dramatically reduced if massive ellipticals were all only a few gigayears old since most of the stellar mass loss occurs just after star formation; however, many or most luminous ellipticals are thought to be very old.

Perhaps the most effective way to preserve the excellent agreement between \( M_\star \) and \( M_X \) in Figure 1 in \( 0.1r_e \lesssim r \lesssim 1r_e \), without constraining the mass dropout profile \( q(r) \), would be to reduce the total mass that has cooled over cosmic time. The most sensitive parameter influencing the cooled mass is the specific rate of stellar mass loss, \( \dot{\alpha}_\star(t) \). Although the total mass of hot gas increases with time due to the continued influx of secondary infalling gas, the mass of hot gas within the optical galaxy originates mostly from stellar mass loss, and the X-ray luminosity there scales as \( L_X \propto \dot{\alpha}_\star(t) \propto t^{-1.3} \) (Appendix B of Tsai & Mathews 1995). Computed models similar to those described here but with arbitrarily reduced \( \dot{\alpha}_\star(t) \) fit the \( n(r) \) and \( \Sigma_X(R) \) data rather well at time \( t_e \) and produce much less cooling dropout. However, \( \dot{\alpha}_\star(t) \) cannot be lowered without also increasing the stellar mass. For all reasonable power-law initial mass functions, \( \dot{\alpha}_\star(t) \) varies inversely with the stellar mass-to-light ratio:

\[
\dot{\alpha}_\star(t) \equiv \frac{dM_\star/\!d t}{M_\star} = \left[ \frac{dM_\star/\!d t}{L_B} \right] \frac{1}{(M_\star/L_B)} \propto \frac{1}{(M_\star/L_B)}.
\]

The physical explanation for the constancy of \( (dM_\star/\!d t)/L_B \) is that both \( L_B \) (dominated by post-main-sequence stars) and \( dM_\star/\!d t \) depend on the instantaneous rate that stars leave the main sequence, so this IMF-dependent factor cancels out (e.g., Renzini & Buzzoni 1986). To illustrate this result, we use the Renzini-Buzzoni procedure and plot in Figure 6 the relationship between \( \dot{\alpha}_\star \) and \( M/L_B \) at time \( t_e = 13 \) Gyr for 84 power-law IMFs with slopes \( \alpha = 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, \) and 1.8, each with lower and upper mass limits of \( m_L = 0.01, 0.032, 0.1, 0.32 \) and \( m_U = 10, 32, 100 \). The remarkable linearity in Figure 6 shows that the quantity in square brackets in the equation above is almost invariant to large changes in the slope or mass limits for power-law IMFs.

Therefore, if \( \dot{\alpha}_\star(t) \) is reduced by 2 or 3 in an attempt to reduce the total dropout mass, the stellar mass (and \( M/L_B \)) must be increased by the same factor; as a result the total mass ejected, \( \int \dot{\alpha}_\star M_\star \, dt \), and the total dropout mass do not change.

6.2. Effect of Galactic Rotation

Although massive ellipticals are not rotationally flattened, they do rotate significantly, e.g., \( \langle v/\sigma \rangle = 0.43 \) for NGC 4472 (Faber et al. 1997). If the hot interstellar gas rotates in the same sense as the bulk of mass-losing stars, stars formed from the cooled gas should form into a disk of scale \( \sim r_c \) (Brighenti & Mathews 1997b), although the development of such disks is likely to be suppressed by the mass dropout process. Nevertheless, to the extent that the cooled gas has a disklike distribution, its global influence on the stellar dynamics in \( r \lesssim 0.4r_e \) would be less than if the same dark mass were distributed spherically. Remarkably, there is no observational evidence at present for rotational

\[ \text{Fig. 6.—Plot of the specific mass-loss rate } \dot{\alpha}_\star(t) \text{ (in } s^{-1}) \text{ against the mass-to-light ratio } M_\star/L_B \text{ in solar units for 84 power-law initial mass functions with varying slopes and mass cutoffs as described in the text.} \]
flattening in the X-ray images of giant ellipticals like NGC 4472.

6.3. Nonbaryonic Dark Matter within \( r_e \)

Dynamical determinations of the mass-to-light ratio from stellar velocities reflect the entire mass within the stellar orbits, including nonbaryonic mass. The NFW halo we use in our models for NGC 4472 agrees with X-ray observations in the extended halo but is slightly too massive near \( r \sim r_e \) relative to the X-ray mass \( M_X(r) \) observationally determined for NGC 4472. This may indicate that dark halos are less centrally peaked than NFW (see Kravtsov et al. 1998). The mass of our NFW halo model contributes about 10% to the dynamical mass-to-light ratio measured within \( r_e / 3 \), but the NFW profile is probably disturbed in this region. When the dominant baryonic mass in \( r \leq r_e \) compressed to form the de Vaucouleurs profile, we expect that the NFW halo was dragged inward and distorted. However, the dark halo cores of the earlier galactic condensations that merged to form the elliptical may have expanded owing to starburst-driven galactic winds. Because of these various counteracting effects, the small nonbaryonic contribution to dynamical mass-to-light determinations is uncertain.

6.4. Contribution of Dropout to "Stellar" \( M/L \)

For all models studied here—based on a wide variety of mass dropout profiles \( q(r) \)—the mass of cooled interstellar gas contributes substantially to the total mass within \( \sim 0.4 r_e \) where the stellar mass-to-light ratio is determined from stellar velocities. If optically dark, low-mass stars form from the cooled gas, the "stellar" mass-to-light ratios in the literature refer to two distinct stellar populations having radically different initial mass functions and spatial distributions. The stellar mass-to-light ratio of the original, optically luminous stellar population is lower than published values indicate.

A complete solution of this problem requires a better understanding of the physics of star formation and the processes that control the stellar IMF. We have assumed here that a Salpeter IMF provides a satisfactory approximation to the original single-burst star formation at early times. Yet we argue that the younger dropout IMF is strongly skewed toward low-mass stars. The IMF has evolved over time. It is possible therefore that the early, more intense mass dropout resulted in a more nearly Salpeter-like IMF, producing a fraction of currently observed luminous stars in ellipticals. If so, this early dropout would not contribute to the excess dropout mass that we find in our models but would have already been included in the original de Vaucouleurs population. High-density, metal-enriched stellar cores in elliptical galaxies may have derived from normal-IMF star formation from early, more intense interstellar cooling. This is similar to assumptions made for dissipative galactic core formation from the convergence of gas following major mergers (Mihos & Hernquist 1996). While such notions cannot be entirely dismissed, the approximate universality of the de Vaucouleurs light profile among ellipticals may argue against a dual formation process for the radial distribution of luminous stars: violent relaxation and cooling flow dropout.

Throughout this discussion, we have assumed that the stellar population formed from cooling flow dropout is optically dark. Although there is little or no evidence that normal massive OB stars (or SN II) are present in elliptical galaxies, it is possible that younger stars having masses up to \( \sim 1-2 M_\odot \) are present and that such intermediate-mass stars could form from the cooled gas (Mathews & Brighenti 1999). This type of dropout stellar population could contribute to the total optical light. If the mass-to-light ratio of dropout and old stellar populations are similar, the dropout component could be difficult to detect by the means we have discussed here and its perturbation on the observed \( M/L_B \) would be greatly lessened. In this case, the dropout population would introduce an additional radial light profile that would differ slightly from that of the old stellar population. The dropout mass profiles in Figure 3 indicate that models 4 and 6 would be rather difficult to detect against the background stellar light. Intermediate-mass dropout stars could therefore provide a satisfactory resolution to the problems we have discussed here.

6.5. Influence of Dropout on the Fundamental Plane

The ensemble of elliptical galaxies is known to have global parameters that deviate slightly from the assumptions of virial equilibrium and homologous structure. The deviation of this fundamental plane relationship is in the sense that the dynamical mass-to-light ratio increases with galactic mass, \( M/L_B \propto M^{0.24} \) (Dressler et al. 1987; Djorgovski & Davis 1987). Such a nonhomologous deviation could, in principle, be produced by the small amount of cooled interstellar gas \( M_{IS} \) provided it increases appropriately with \( M_* \). To test this idea, we performed an identical hydrodynamic calculation for an elliptical galaxy having a mass one-fourth that of NGC 4472. The dark halo mass was also reduced by the same factor but the cosmological environment and mass dropout distribution were identical to those used for NGC 4472, scaled to a smaller \( r_e \). We found that the amount of mass dropout \( M_{IS} \) is higher in smaller ellipticals relative to the total baryonic mass \( M_* \). This is opposite to the trend observed in the fundamental plane. However, if hot gas and dark matter in the outer halos of smaller ellipticals are tidally stripped in group environments, as suggested by Mathews & Brighenti (1999b), then the mass of cooled gas could be reduced and its effect on the fundamental plane would be reduced. Nevertheless, explanations of the deviations of the fundamental plane from virial scaling must recognize the possible additional influence of dropout mass, regardless of the trend of \( M_{IS}/M_* \) with \( M_* \).

6.6. Conclusions

Using simple spherical gasdynamical models for the evolution of interstellar gas and data from the well-observed elliptical NGC 4472, we reach the following conclusions:

1. If the hot interstellar gas cools only in the very center of NGC 4472 for \( \sim 10 \) Gyr, the total accumulated mass would be \( \gtrsim 10 \) times larger than the mass of the central black hole observed. If such large concentrated masses were generally present in bright ellipticals, interstellar gas in \( r \lesssim 0.1 r_e \) would be compressed and heated to temperatures greater than 1 keV. Such hot thermal cores are not generally observed. We conclude that the cooling dropout in massive ellipticals must occur before the gas reaches the galactic center. The hypotheses of distributed mass dropout and low-mass star formation were proposed many years ago (Fabian et al. 1982; Thomas 1986; Cowie &
Binney 1977; Vedder et al. 1988; Sarazin & Ashe 1989; Ferland et al. 1994). However, these historical arguments were generally based on the notion that mass dropout would help reduce computed X-ray surface brightness profiles at small projected radii, as required by the observations, but we have shown here that in some cases enhanced dropout at small galactic radii can cause $\Sigma_{X}$ to increase, not decrease. (The total bolometric X-ray luminosity $L_{X}$ should always be lower in distributed cooling models since the hot gas experiences only a fraction of the galactic potential.) The best arguments for distributed cooling dropout are (a) limits on the central black hole mass and (b) the absence of rotational flattening in X-ray images.

2. We have considered a wide variety of possible mass profiles for the radial deposition of cooled interstellar gas in NGC 4472. The dropout mass is assumed to be optically dark, consistent with the formation of very low mass stars. In every case, the (stellar plus dropout) mass-to-light ratio at $r_{*}/3$ significantly exceeds the mass-to-light ratio determined from stellar velocities. If the dropout mass is optically dark, dynamical mass-to-light ratios in luminous ellipticals should be substantially enhanced by dark baryonic matter. In this case, the true $M/L_{B}$ for luminous stars may be $\sim 30\%$ smaller than published values.

3. The excellent agreement between the X-ray and “stellar” mass in NGC 4472 shown in Figure 1 (and also NGC 4649) in the range $0.1r_{*} \leq r \leq r_{*}$ may be a coincidence if our estimates of the cooling flow dropout mass are correct and if this mass is nonluminous.

4. Dynamical mass-to-light determinations within $r_{*}$ refer to a superposition of two stellar populations: an old luminous population with a de Vaucouleurs galactic profile and a younger population having a bottom-heavy IMF and a different galactic mass profile. If the younger population is optically dark, the mass-to-light ratio is not likely to be constant with galactic radius within $r_{*}$.

5. It is not possible to reduce the total amount of mass deposited from the cooling flow simply by lowering the specific rate of stellar mass loss $\alpha_{*}(t) \equiv (dM_{*}/dt)/M_{*}$. For all reasonable power-law initial mass functions, we show that $\alpha_{*} \propto (M_{*}/L_{B})^{-1}$. For given $L_{B}$, larger stellar masses $M_{*}(r)$ must accompany lower values of $\alpha_{*}$ so the total amount of mass ejected from stars $\propto \int \alpha_{*}(t)M_{*} \, dt$ is nearly independent of the IMF.

6. Among the models we consider, those with centrally concentrated mass dropout perform best in minimizing the overall disagreement with the central $M/L_{B}$ and the X-ray–determined mass in $0.1r_{*} \leq r \leq r_{*}$. Constant $q$ models in which the dropout is proportional to the local gas emissivity at every radius deposit less mass in $0.1r_{*} \leq r \leq r_{*}$ but may have gas temperatures that are too low ($q \geq 4$) or central masses that are too large ($q \leq 1$).

7. Even in the presence of mass dropout, the computed central interstellar gas densities and X-ray surface brightnesses $\Sigma_{X}(R)$ are generally too large. Such deviations would be reduced if the hot gas is partially supported in $r \leq 0.1r_{*}$ by magnetic or other nonthermal pressure associated with the extended radio source.

8. If the stellar population formed from cooled interstellar gas extends to intermediate masses, $\sim 1-2$ $M_{\odot}$, its mass-to-light ratio may blend with that of the older population. In this case, the dropout mass would already be represented in the de Vaucouleurs profile representing the stellar mass distribution in our models. Dynamical determinations of $M/L_{B}$ would be a weighted mean of the two populations. If the dropout stellar population is luminous, some of the difficulties we have discussed here would be alleviated but not those regarding $\Sigma_{X}(R)$.

9. If the influence of rotation and nonthermal pressure can be understood, high-resolution images of the central regions of elliptical galaxies and X-ray satellite may detect the presence of dark baryonic dropout material and provide an accurate determination of the mass-to-light ratio of the old stellar population.

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