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THE HOT GAS CONTENT OF LOW-LUMINOSITY EARLY-TYPE GALAXIES AND THE IMPLICATIONS REGARDING SUPERNOVA HEATING AND ACTIVE GALACTIC NUCLEUS FEEDBACK
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ABSTRACT
We have analyzed Chandra observations of 18 low-luminosity early-type galaxies with $L_B \leq 3 \times 10^{10} L_{\odot B}$. Thermal emission from hot gas with temperatures between 0.2 and 0.8 keV comprises 5%–70% of the total 0.5–2.0 keV emission from these galaxies. We find that the total X-ray luminosity from LMXBs (resolved plus the power-law component of the unresolved emission) scales roughly linearly with the $K$-band luminosity of the galaxies with a normalization comparable to that found in more luminous early-type galaxies. All of the galaxies in our sample are gas-poor, with gas masses much less than that expected from the accumulation of stellar mass loss over the lifetime of the galaxies. The average ratio of gas mass to stellar mass in our sample is $M_{gas}/M_* = 0.001$, compared to more luminous early-type galaxies that typically have $M_{gas}/M_* = 0.01$. The time required to accumulate the observed gas mass from stellar mass loss in these galaxies is typically $3 \times 10^8$ yr. Since the cooling time of the gas is longer than the replenishment time, the gas cannot be condensing out of the hot phase and forming stars, implying that the gas is most likely being expelled from these galaxies in a wind. The one exception to this is NGC 4552, which is the most optically luminous galaxy in our sample and has the highest gas content. Using recent estimates of the Type Ia supernova rate and AGN heating rate in early-type galaxies, we find that, on average, heating by Type Ia supernovae should exceed AGN heating in galaxies with $L_B \leq 3 \times 10^{10} L_{\odot B}$. We also find that heating by Type Ia supernovae is energetically sufficient to drive winds in these galaxies, even if the present Type Ia supernova rate is overestimated by a factor of 2 or the present stellar mass-loss rate is underestimated by a factor of 2.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: ISM — X-rays: binaries — X-rays: galaxies — X-rays: ISM

1. INTRODUCTION

Heating by supernovae and active galactic nuclei (AGNs) is thought to play an important role in galaxy formation, generating the observed correlation between the bulge mass of a galaxy and the mass of the central supermassive black hole, the upper mass cutoff of galaxies, and reheating the gas in galaxies, groups, and clusters. In order to reconcile the predictions of the cold dark matter hierarchical clustering scenario with the observed luminosity function of galaxies and their mass-to-light ratios, it has been proposed that 2 supernova feedback regulates star formation in galaxies less luminous than about $3 \times 10^{10} L_{\odot B}$, while AGN feedback regulates star formation in more massive galaxies (e.g., White & Frenk 1991; Bower et al. 2005; Croton et al. 2006). Only Type II supernovae provide a natural feedback mechanism, due to the short time delay between the onset of star formation and the first supernova. While Type Ia supernovae (SNe Ia) cannot provide a feedback mechanism that regulates concurrent star formation, SNe Ia can play a significant role in the fate of gas shed by evolving stars in low-mass galaxies long after star formation ceases.

Einstein observations showed that the bulk of the X-ray emission from optically luminous early-type galaxies arises from hot gas in hydrostatic equilibrium (Forman et al. 1985). A harder X-ray component, more prevalent among low-luminosity early-type galaxies, was detected by ASCA and assumed to arise from low-mass X-ray binaries (LMXBs) due to the old stellar population in these systems (Kim et al. 1992). Based on the analysis of ASCA data, White et al. (2002) found that the luminosity of the hard X-ray component was more strongly correlated with the luminosity in globular clusters than with the total optical luminosity of the galaxies. Chandra, with its superior angular resolution, has resolved populations of point sources in many early-type galaxies (e.g., Sarazin et al. 2000; Angelini et al. 2001; Kraft et al. 2001; Blanton et al. 2001) and found that 20%–80% of the point sources reside in globular clusters (Sarazin et al. 2003).

While the hot gas content of X-ray luminous early-type galaxies has been well studied by Chandra and previous X-ray telescopes, little is known about the properties of the gas in less luminous early-type galaxies. In low-luminosity early-type galaxies, the X-ray emission from LMXBs can exceed the thermal emission from hot gas, so it is imperative that the LMXBs be detected and excised from the analysis of the diffuse emission. Theoretical models concerning the evolution of early-type galaxies show that for typical SN Ia rates, early-type galaxies fainter than $M_B \approx -20$ should possess SN Ia driven galactic winds (e.g., David et al. 1990, 1991). In addition to heating by SNe Ia, AGN heating may also expel a significant portion of the gas shed by evolving stars in the shallow potential well of low-luminosity galaxies. Chandra has detected X-ray cavities filled with radio-emitting plasma and AGN-driven shocks in many elliptical galaxies and clusters (e.g., McNamara et al. 2000; Finoguenov & Jones 2002; Fabian et al. 2003; Blanton et al. 2003; Nulsen et al. 2005a, 2005b; Forman et al. 2005). Based on the analysis of cavities found in a sample of galaxies, groups, and clusters, Birzan et al. (2004) determined that the mechanical power of AGNs can be up to $10^9$ times their radio power. Thus, the thermal and dynamic properties of the hot gas in low-luminosity early-type galaxies are sensitive probes of the present SN Ia rate and AGN activity in these galaxies.

This paper is organized in the following manner. In § 2, we present our low-luminosity early-type galaxy sample. Section 3 contains the details of our Chandra data reduction. The spectroscopic results for the LMXBs and diffuse emission are discussed in § 4, and the observed scaling between the total X-ray luminosity of the LMXB population and the $K$-band luminosity...
of the galaxies is presented in § 5. Sections 6 and 7 discuss the properties of the hot gas, the inferred characteristics of the galactic winds, and the implications regarding the Fe abundance in galaxies with galactic winds. In § 8, we examine the relative importance of AGN and SN Ia heating in these galaxies. Possible origins of the large scatter in the observed gas properties among the galaxies are discussed in § 9, and the main results of our paper are summarized in § 10.

2. GALAXY SAMPLE

C. Jones et al. (2006, in preparation) have compiled a sample of early-type galaxies that have been observed by the Chandra X-ray observatory. We initially extracted a sample of galaxies with $M_B$ between $-18$ and $-20.4$ (corresponding to $L_B$ between $3 \times 10^{10}$ and $3 \times 10^{10} L_{\odot}$). Galaxies with nearby companions and total ACIS exposure times less than 5 ks were then excluded from our sample. After a preliminary analysis of the Chandra data, we also excluded galaxies with fewer than 100 total net counts from further analysis. Our final sample of 18 low-luminosity early-type galaxies is shown in Table 1 along with their optical and infrared properties and cleaned ACIS exposure times. The absolute blue magnitudes given in Table 1 are computed from $m_B(T^0)$ (RC3; de Vaucouleurs et al. 1991) and the distance moduli given in Tonry (2001), if available. Otherwise, we use the corrected redshift in Faber et al. (1989), or, finally, the uncorrected redshifts. We use $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ throughout. The K-band apparent magnitudes and luminosities given in Table 1 are derived directly from the Two Micron All Sky Survey (2MASS) K-band images and are computed within the same aperture used to extract the X-ray spectrum from the galaxy. The stellar velocity dispersion is obtained from Faber et al. (1989), if available, otherwise we use the average stellar velocity dispersion from the literature as given in the LEDA catalog.

3. DATA REDUCTION

All Chandra archival observations of the galaxies in our sample were reprocessed with CIAO 3.2.2 and CALDB 3.1.0 and screened for background flares. Fifteen of the galaxies in our sample were imaged on the S3 chip, two on the I3 chip, and one on the S2 chip. Multiple exposures of the same galaxy were combined into a single exposure. For each galaxy, we generated a 0.3–6.0 keV image with a detection threshold of $10^{-6}$ to generate the point-source regions. Unlike more luminous early-type galaxies, the galaxies in our sample have little hot gas, so the point-source detection efficiency is fairly uniform across the galaxies. There is some area on the ACIS chip beyond the $D_{25}$ optical isophote with the $D_{25}$ edge at full spatial resolution for the chip on which the target was imaged.

We then ran the CIAO wavdetect tool on each 0.3–6.0 keV image with a detection threshold of $10^{-6}$ to generate the point-source regions. Unlike more luminous early-type galaxies, the galaxies in our sample have little hot gas, so the point-source detection efficiency is fairly uniform across the galaxies. There is some area on the ACIS chip beyond the $D_{25}$ optical isophote with the $D_{25}$ edge at full spatial resolution for the chip on which the target was imaged.

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4. SPECTRAL ANALYSIS

Using the point-source regions generated by wavdetect along with the $D_{25}$ optical isophote, we extracted three spectra for each galaxy: (1) a spectrum containing the combined emission from all detected nonstellar point sources within the $D_{25}$ isophote, (2) a spectrum of the unresolved emission within $D_{25}$ (i.e., the emission outside of the detected source regions), and (3) a background spectrum from the unresolved emission beyond the $D_{25}$ isophote. A point source is identified as an AGN if it is located within $2.0$ of...
the centroid of the galaxy as determined from the 2MASS K-band image. None of our galaxies has more than one source within this region. The spectra for the detected sources and the unresolved emission were binned to a minimum of 20 counts per bin, and the corresponding photon-weighted response and area files were generated using the CIAO tasks mkacisrmf and mkwarf.

4.1. Point-source Population

The background-subtracted (i.e., the unresolved component of the X-ray background) spectra of the combined emission from the detected nonnuclear point sources with more than 100 net counts were fitted to an absorbed power-law model with the absorption fixed at the galactic value. Our analysis shows that the emission from the binary populations is well fitted by a power-law spectrum with $\Gamma \approx 1.6$ (see Table 2). This result is consistent with the spectral analysis of the combined emission from LMXBs in a sample of 15 early-type galaxies analyzed by Irwin et al. (2003).

In cases where the combined emission from the detected point sources results in fewer than 100 net counts, the fluxes are derived assuming galactic absorption and $\Gamma = 1.6$. To estimate the number of background point sources and the integrated flux, we used the 0.5–2.0 keV luminosity function derived from the Chandra Deep Field–South (Rosati et al. 2002) and the 3 $\sigma$ point-source detection threshold in each observation. The total number of detected nonnuclear point sources and the expected number of background AGN above the 3 $\sigma$ detection limit are shown in Table 2. The resulting background-subtracted (both unresolved and AGN) 0.5–2.0 keV flux and luminosity for the combined point-source emission in each galaxy are given in Table 2. Due to the small angular extent of the galaxies, variations in the number of background AGN do not have a significant effect on the derived fluxes. There are also very few photons from the diffuse background component within the source regions. The primary uncertainty in the derived X-ray flux is the uncertainty in the spectral model. For $\Gamma$ between 1.2 and 2.0, the estimated 0.5–2.0 keV flux varies by 25%.

### 4.2. Diffuse Emission

The unresolved diffuse emission in each observation must contain some emission from LMXBs with fluxes below the point-source detection limit. The low gas temperature ($kT \approx 0.3$–0.6 keV) in these galaxies makes it easier to separate the thermal and power-law components compared to more X-ray luminous early-type galaxies, which typically have gas temperatures around 1 keV. We first fit the diffuse emission with an absorbed power-law model. Except for NGC 1389, NGC 821, and NGC 4251, the best-fit index is significantly steeper than that obtained from fitting the combined emission from the detected point sources (see Table 3), indicating the presence of a diffuse soft component.
component. We then fit the diffuse spectra with an absorbed power-law plus MEKAL model with the absorption frozen at the Galactic value and the abundance of heavy elements frozen at the solar value (see the results in Table 4). In all but three cases (NGC 1389, NGC 821, and NGC 4251), adding a thermal component improved the fit at greater than the 95% confidence level, based on a $\chi^2$/dof-test. The resulting best-fit power-law indices in the two-component model are consistent with those derived from fitting the combined emission from the detected point sources. This shows that the spectral index of LMXBs does not vary significantly with luminosity, which is consistent with Chandra observations of the lowest luminosity LMXBs in our Galaxy (Wilson et al. 2003). For NGC 1389, NGC 821, and NGC 4251, we determined the 90% upper limit on the thermal flux by increasing the normalization of the MEKAL model until the resulting $\chi^2$ increased by 2.71 compared to the best fit with a pure power-law model.

Besides emission from hot gas, there are other potential sources for the unresolved soft X-ray emission, including supersoft sources, M stars, and RS CVn systems. Pellegrini & Fabbiano (1994) showed that both K-M main-sequence stars, due to the reduced rotation rate in old stars, and RS CVn systems are unlikely to produce a significant component of the soft X-ray emission in early-type galaxies. Supersoft sources are characterized by blackbody emission with $kT < 100$ eV. Supersoft sources are probably a combination of several types of objects, including postnovae hot white dwarfs, symbiotics, pre--white dwarfs in planetary nebulae, accreting white dwarfs, and possibly accreting intermediate-mass black holes (Kahabka & van den Heuvel 1997). A scatter plot of gas temperature versus stellar velocity dispersion for our galaxy sample is shown in Figure 1. The solid line in Figure 1 is the relation found by O’Sullivan et al. (2003) for a sample of more X-ray luminous early-type galaxies with typical velocity dispersions between 250 and 350 km s$^{-1}$. While there is significant scatter in Figure 1, the relation between gas temperature and velocity dispersion in our sample of galaxies is in reasonable agreement with that observed in 50% hotter systems, providing strong evidence that the soft X-ray emission in our sample arises from hot gas. Gas shed by evolving stars thermalizes at the temperature associated with the stellar velocity dispersion of the stars ($T_g = \mu m_p \sigma^2 /k$), which is shown as a dashed line in Figure 1. The ratio of energy per unit mass in the stars to that in the gas, $\beta_{pec} = T_g/T_g$, varies from 0.3 to 1 in our sample, which is comparable to values found in more X-ray luminous early-type galaxies, giving further support to a gaseous origin for the soft unresolved emission.

We also can use the Chandra data directly to place limits on the contribution to the diffuse emission from supersoft sources.
Chandra has detected supersoft sources in many galaxies (Sarazin 2000; Pence et al. 2001; Swartz et al. 2002; Di Stefano & Kong 2004) and there appears to be a general trend that supersoft sources are more common in the spiral arms of late-type galaxies than in bulge-dominated systems. Sarazin et al. (2000) identified three supersoft sources in NGC 4697 by using hardness ratios. Di Stefano & Kong (2004) fitted the combined emission from the three supersoft sources in NGC 4697 to an absorbed blackbody model, and obtained a temperature of 7.0 keV flux of 1 $10^{38}$ ergs cm$^{-2}$ s$^{-1}$. Using this spectral model, and converting between bandpasses, gives a 0.5–2.0 keV flux of 6.0 $10^{-15}$ ergs cm$^{-2}$ s$^{-1}$, which is only 2% of the total resolved 0.5–2.0 keV flux of NGC 4697 given in Table 2. Adding an 80 eV blackbody component in the spectral analysis of the diffuse emission does not significantly improve the fit in any of the galaxies in our sample. For NGC 4697, the 90% upper limit on the 0.5–2.0 keV flux of an 80 eV blackbody component is 6.0 $10^{-15}$ ergs cm$^{-2}$ s$^{-1}$, which is twice the flux of the resolved supersoft sources, but only 4% of the flux in the thermal component of the unresolved emission.

5. SCALING BETWEEN $L_X$, LMXB AND THE K-BAND LUMINOSITY

Earlier studies based on Einstein and Röntgensatellit (ROSAT) observations showed that $L_X \propto L_B^2$ for early-type galaxies more luminous than $L_B \approx 3 \times 10^{10} L_\odot$ and $L_X \propto L_B$ for less luminous galaxies (Forman et al. 1985; Trinchieri & Fabbianio 1985; O’Sullivan et al. 1991). The different slopes were thought to arise from the competition between the two primary sources of X-rays in early-type galaxies, with emission from LMXBs dominating in low-luminosity galaxies and thermal emission from hot gas dominating in more luminous galaxies. Observations of early-type galaxies by Chandra are able to study these two components separately. With the availability of 2MASS data, it is more appropriate to use $L_K$ instead of $L_B$, since it is a better proxy for stellar mass. The combined 0.5–2.0 keV luminosity of only the resolved LMXBs is plotted against the $K$-band luminosity of the galaxies in Figure 2 and the total 0.5–2.0 keV luminosity of the LMXBs ($L_{LMXB} = L_{X,res} + L_{X,unres}$) is plotted against the $K$-band luminosity of the galaxies in Figure 3. Due to the range in sensitivity among the observations (see Table 2), there is significant scatter in Figure 2. By combining the power-law component of the unresolved emission with the resolved LMXB emission, the scatter is significantly reduced in Figure 3, and there is an overall linear trend between $L_{LMXB}$ and $L_K$. The most X-ray luminous galaxy in Figures 2 and 3 is NGC 4552, which is discussed more extensively in §9. Fitting a power law to the data in Figure 3 yields a best fit of

$$L_{LMXB} = 3.7 \times 10^{38} \left( \frac{L_K}{10^{10} L_\odot} \right)^{0.81} \text{ergs s}^{-1},$$

which is shown as a solid line in Figure 3. Several studies have shown that the spatial distribution of LMXBs follows the light in early-type galaxies (Sarazin et al. 2001; Gilfanov 2004; Jordan et al. 2004), so our estimate of $L_{LMXB}/L_K$ should be valid within any aperture.

Both Colbert et al. (2004) and Kim & Fabbianio (2004) estimated the ratio of $L_{LMXB}$ to $L_K$ for samples of more X-ray luminous early-type galaxies. In these studies, $L_{LMXB}$ was computed in the 0.3–8.0 keV bandpass assuming a count rate conversion factor appropriate for power-law spectra with $\Gamma = 1.7$–1.8 and Galactic absorption. The difference between the spectral index used in our work and the one in these studies does not make a significant difference in the derived luminosities. However, their 0.3–8.0 keV luminosities should be 3 times our 0.5–2.0 keV luminosities. Both studies only included the emission from nonnuclear point sources within the D25 isophote. Kim & Fabbianio computed $L_{LMXB}$ by integrating over the galaxy’s LMXB luminosity function. Colbert et al. derived a relation of $L_{LMXB} = 1.3 \times 10^{-4} L_K$, where $L_K = \nu L_\nu$. From the 2MASS documentation, $\nu L_\nu (m_K = 0) = 9.27 \times 10^{-7}$ ergs cm$^{-2}$ s$^{-1}$. Rewriting their expression in terms of $L_{LMXB}$, and adjusting for bandpass differences, gives a coefficient in equation (1) of 2.3 $10^{38}$ ergs s$^{-1}$, which is 50% lower than our...
estimate. After correcting for bandpass differences, the ratio of \( L_{\text{LMXB}} \) to \( L_K \) in Kim & Fabbiano is a factor of 1.8 higher than our result. Thus, within a factor of 2, we find the same ratio of \( L_{\text{LMXB}} \) to \( L_K \) in our sample as that found in more X-ray luminous systems.

Previous studies have suggested that \( L_{\text{X,LMXB}} \) is better correlated with the total luminosity in globular clusters (White et al. 2002) and that the dispersion in the \( L_{\text{X,LMXB}}-L_K \) relation is correlated with the specific frequency of globular clusters, \( S_N \) (Kim & Fabbiano 2004). A search of the literature only uncovered published values of \( S_N \) for half of the galaxies in our sample, and most of these estimates have large errors, so we cannot investigate the dependence of \( L_{\text{X,LMXB}} \) on \( S_N \) in our sample.

6. THE HOT GAS CONTENT

There is significant scatter in \( L_{\text{X,gas}} \) compared to \( L_{\text{X,LMXB}} \) with a factor of 100 variation in \( L_{\text{X,gas}} \) for a given \( L_K \) (see Fig. 4). The ratio of \( L_{\text{X,gas}} / L_{\text{X,LMXB}} \) also shows significant scatter and varies from 0.04 to 2.2 (see Fig. 5). We also divided the sample into ellipticals \( (T < -3) \) and S0s \( (T > -3.0) \). The average \( L_{\text{X,gas}} \) is essentially the same for ellipticals and S0s, but the ellipticals have a greater dispersion (see Fig. 4). Early-type galaxies can be classified as “core” or “cuspy” depending on their inner stellar surface brightness profile. Based on \( ROSAT \) observations, Pellegrini (2005) found that for a given optical luminosity, core early-type galaxies are more X-ray luminous than cuspy galaxies. We searched the literature for \( HST \)-derived stellar surface brightness profiles of the galaxies in our sample, but only found results for 8 galaxies, so we cannot draw any general conclusions. There is a fairly strong correlation between \( L_{\text{X,gas}} \) and \( kT \) among X-ray luminous early-type galaxies (O’Sullivan et al. 2003). Our sample of lower luminosity galaxies, however, does not show such a correlation (see Fig. 6), suggesting that nongravitational heating mechanisms have a more significant impact on the gas properties of lower luminosity galaxies.

The gas density and mass can be estimated from the emission measure of the best-fit MEKAL model to the diffuse emission along with an assumption about the spatial distribution of the gas. The soft photon statistics in the \( Chandra \) data are insufficient to permit an empirical determination of the surface brightness profile of each galaxy. Past studies have shown that the X-ray surface brightness of luminous early-type galaxies is well fitted by a \( \beta \) model with \( \beta \approx 0.5 \) and a core radius between 1 and 3 kpc (Forman et al. 1985). David et al. (1990, 1991) generated a grid of elliptical galaxy models with different kinematic states of the hot gas (e.g., cooling flows, partial winds, total subsonic winds, and total transonic winds) and found that the surface brightness profile of these models could be characterized with \( \beta \) between 0.3 and 0.5. Table 5 contains the derived central gas density and

![Fig. 4](image1.png)

Fig. 4.— Scatter plot of the 0.5–2.0 keV luminosity of the thermal component of the diffuse emission \( (L_{\text{X,gas}}) \) vs. the \( K \)-band luminosity of the galaxies. Triangles correspond to 90% upper limits. Filled symbols represent ellipticals \( (T < -3) \) and open symbols represent lenticulars \( (T > -3) \).

![Fig. 5](image2.png)

Fig. 5.— Ratio of the gas luminosity to total LMXB luminosity vs. the \( K \)-band luminosity.

![Fig. 6](image3.png)

Fig. 6.— Scatter plot of the 0.5–2.0 keV luminosity of the thermal component of the diffuse emission \( (L_{\text{X,gas}}) \) against the best-fit temperature. The errors bars on the temperature are shown at the 1 \( \sigma \) confidence level.
mass in each galaxy assuming $\beta = 0.5$ and a core radius of 1 kpc. This calculation also assumes that the diffuse emission arises from within a circular region centered on the galaxy with a radius of $R_m$ (given in Table 5) that has the same area as that in the region used to extract the X-ray spectrum of the diffuse emission. Varying $\beta$ between 0.3 and 0.67 or the core radius between 1 and 10 kpc only changes the estimated gas mass by 40%.

All of the early-type galaxies in our sample are gas poor with an average $M_{\text{gas}} \approx 3 \times 10^7 M_\odot$ (see Table 5). Based on stellar evolution models of early-type galaxies, Bell & de Jong (2001) derived an expression of $\log (M_*/L_K) = -0.692 + 0.652(B-V)$, where $M_*$ is the stellar mass. The mean $B-V$ in our sample is 0.9, which gives $M_*/L_K = 0.8 M_\odot/L_\odot K$ (consistent with dynamical measurements of a sample of early-type galaxies by Humphrey et al. 2006) and $M_{\text{gas}}/M_* = 8.0 \times 10^{-4}$. A cumulative histogram of $M_{\text{gas}}/M_*$ for our sample is shown in Figure 7. For comparison, Fukazawa et al. (2006) recently analyzed Chandra observations of 53 X-ray luminous early-type galaxies and found average values of $n_e = 0.1 \, \text{cm}^{-3}$, $M_{\text{gas}} = 3 \times 10^9 M_\odot$, and $M_{\text{gas}}/M_* = 0.01$. Figure 8 shows that there is significant scatter in $M_{\text{gas}}/M_*$ for a given $L_K$ among the galaxies in our sample, but even the most gas-rich system in our sample (NGC 4552) does not have as high a gas content as the mean value in the Fukazawa et al. sample.

![Fig. 7](image-url)  
**Fig. 7.** Cumulative histogram of $M_{\text{gas}}/M_*$.  

![Fig. 8](image-url)  
**Fig. 8.** Scatter plot of the ratio of gas mass to stellar mass ($M_{\text{gas}}/M_*$) vs. the $K$-band luminosity of the galaxies.

### Table 5: Hot Gas Content

| Name            | $R_m$  | $n_e$  | $M_{\text{gas}}$ | $t_c$ | $t_r$ |
|-----------------|--------|--------|------------------|-------|-------|
| ESO 0428-6014   | 4.8    | $9.5 \times 10^{-3}$ | $2.0 \times 10^7$ | 0.065 | 3.1 $\times 10^8$ | 2.2 $\times 10^9$ |
| NGC 821         | 7.0    | $<1.3 \times 10^{-2}$ | $<5.0 \times 10^7$ | 0.158 | $<3.2 \times 10^8$ | $\ldots$ |
| NGC 1023        | 6.9    | $5.6 \times 10^{-3}$ | $2.2 \times 10^7$ | 0.152 | $1.4 \times 10^8$ | $5.4 \times 10^8$ |
| NGC 1386        | 5.7    | $1.8 \times 10^{-2}$ | $4.9 \times 10^7$ | 0.062 | $7.9 \times 10^8$ | $7.0 \times 10^8$ |
| NGC 1389        | 5.7    | $<1.4 \times 10^{-2}$ | $<3.9 \times 10^7$ | 0.070 | $<5.5 \times 10^8$ | $\ldots$ |
| NGC 2434        | 7.5    | $2.1 \times 10^{-2}$ | $9.3 \times 10^7$ | 0.133 | $7.0 \times 10^8$ | $1.4 \times 10^8$ |
| NGC 2787        | 3.9    | $5.6 \times 10^{-3}$ | $8.2 \times 10^6$ | 0.026 | $3.1 \times 10^8$ | $1.6 \times 10^8$ |
| NGC 3115        | 5.8    | $5.5 \times 10^{-3}$ | $1.6 \times 10^7$ | 0.161 | $9.9 \times 10^7$ | $4.6 \times 10^7$ |
| NGC 3245        | 7.3    | $1.1 \times 10^{-2}$ | $4.6 \times 10^7$ | 0.107 | $4.3 \times 10^8$ | $1.6 \times 10^8$ |
| NGC 3377        | 6.5    | $4.7 \times 10^{-3}$ | $1.7 \times 10^7$ | 0.049 | $3.5 \times 10^8$ | $2.6 \times 10^8$ |
| NGC 3379        | 7.7    | $3.1 \times 10^{-3}$ | $1.4 \times 10^7$ | 0.132 | $1.1 \times 10^8$ | $1.3 \times 10^8$ |
| NGC 3608        | 9.3    | $1.4 \times 10^{-2}$ | $9.0 \times 10^7$ | 0.094 | $9.6 \times 10^8$ | $1.4 \times 10^8$ |
| NGC 4251        | 6.8    | $<8.4 \times 10^{-3}$ | $<3.2 \times 10^7$ | 0.120 | $<2.7 \times 10^8$ | $\ldots$ |
| NGC 4435        | 4.0    | $7.7 \times 10^{-3}$ | $1.2 \times 10^7$ | 0.043 | $2.8 \times 10^8$ | $1.4 \times 10^8$ |
| NGC 4459        | 7.0    | $1.2 \times 10^{-2}$ | $4.7 \times 10^7$ | 0.136 | $3.4 \times 10^8$ | $1.6 \times 10^8$ |
| NGC 4552        | 10.7   | $3.2 \times 10^{-2}$ | $2.5 \times 10^8$ | 0.189 | $1.3 \times 10^9$ | $1.3 \times 10^9$ |
| NGC 4697        | 9.1    | $1.3 \times 10^{-2}$ | $8.2 \times 10^7$ | 0.164 | $5.0 \times 10^8$ | $1.5 \times 10^8$ |
| NGC 5866        | 6.7    | $1.6 \times 10^{-2}$ | $5.9 \times 10^7$ | 0.163 | $3.6 \times 10^8$ | $1.0 \times 10^8$ |

**Notes.**—Galaxy name, the radius of a circular aperture that has the same area as the region used to extract the diffuse X-ray spectrum ($R_m$), central electron number density ($n_e$), gas mass ($M_{\text{gas}}$) within $R_m$, stellar mass-loss rate ($\dot{M}_*$) estimated from $L_K$ in Table 1, the time to accumulate the observed gas mass given the present stellar mass-loss rate ($t_r$), and the average radiative cooling time of the gas ($t_c$).
For a Salpeter initial mass function, stars shed approximately 30% of their initial mass over a Hubble time, which gives an average ejected mass of $2 \times 10^{10} M_\odot$ per galaxy in our sample. Very little of this gas can accrete into the central supermassive black hole. Based on the average stellar velocity dispersion in our sample ($\sigma_v = 200$ km s$^{-1}$) and the observed correlation between the central black hole mass and $\sigma_v$, (Gebhardt et al. 2000), the average $M_{\text{bl}}$ in our sample should be approximately $1.2 \times 10^8 M_\odot$. To determine how long it takes to accumulate the observed gas mass, we use a present day stellar mass-loss rate from asymptotic giant branch stars of $\dot{M}_\star = 0.078(L_\odot/10^{10} L_\odot) M_\odot$ yr$^{-1}$, which is consistent with the derived stellar mass-loss rate from a sample of nine ellipticals observed by the Infrared Space Observatory (Athey et al. 2002). Converting this stellar mass-loss rate to the K-band and using $L_K$ within the same aperture used to extract the diffuse spectrum (see Table 1), we find that the time to accumulate the derived gas mass in these galaxies is $t_e \approx 1 - 3 \times 10^8$ yr (see Table 5). The typical cooling time of the gas [$t_c = 5kTm_{\text{gas}}/(2\mu m_p L_{\text{bol}})$] shown in Table 5 is $t_c \approx 10^9$ yr. Since the cooling time is longer than the replenishment time, the gas cannot be condensing out of the hot phase and forming stars. Thus, most of the gas shed by evolving stars must have been expelled from these galaxies in a wind. The only exception to this is NGC 4552 (M89), which is the most optically luminous galaxy in our sample, has the highest gas content, and is located in the densest environment. The Chandra image of NGC 4552 shows that it has a significant gaseous corona and that it is presently being ram pressure stripped of its gas as it falls into the Virgo cluster (Machacek et al. 2005).

There have been many theoretical studies regarding the dynamical evolution of the hot gas in early-type galaxies (e.g., Mathews & Baker 1971; Loewenstein & Mathews 1987; David et al. 1990, 1991; Cioffi et al. 1991, Pellegrini & Fabbiano 1994; Brighenti & Mathews 1999). The primary quantity that determines the present dynamic state of the gas is the ratio of the mass-averaged temperature of the stellar ejecta to the depth of the gravitational potential well of the galaxy. The mass-averaged temperature of stellar ejecta is given by $T_e = \frac{M_{\text{SN}} \alpha T_{\text{SN}}}{M_\star}$, where $T_{\text{SN}} = 2\mu m_{\text{e}}E_{\text{SN}}/3(M_\odot)$ and $M_{\text{SN}} = M_{\text{SN}}/(3M_\odot)$. Using $E_{\text{SN}} = 10^{51}$ ergs and $M_{\text{SN}} = 1.4 M_\odot$ gives $T_{\text{SN}} = 150$ keV per particle. A large grid of models has been generated over the past 20 years covering a range of galaxy masses, SN Ia rates, stellar mass functions, and mass-to-light ratios. Most models have used SN Ia rates between 1/4 and 1 times Tammann’s (1982) rate of $\nu_{\text{SN Ia}} = 0.88h^2$ SNU [where $h$ is the Hubble constant in units of 100 km s$^{-1}$ Mpc$^{-1}$ and a SNU $= 1/100$ yr(10$^{10}$ L$_{\odot}$)$^{-1}$] and a stellar mass-loss rate of approximately $\dot{M}_\star = 0.15(L_\odot/10^{10} L_\odot) M_\odot$ yr$^{-1}$ (Faber & Gallagher 1976). Converting to $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, these rates give $T_e = 1.5 - 6.0$ keV per particle. In the Appendix, we show that the minimum energy required to remove the gas shed by stars in a wind is equal to the mass-averaged binding energy of the injected gas (eq. [A19]). We computed this minimum energy in detail for NGC 1023, which has a stellar velocity dispersion close to the mean in our sample, assuming a Navarro et al. (1996) distribution with a concentration parameter of 10 for the dark matter and a King model for the stellar distribution with a core radius of 5179 (Jarrett et al. 2003). This calculation gives a minimum energy of 2.01 keV per particle, which is equal to $7.2\sigma^2$ in NGC 1023.

If the gas is in a steady state wind, then $M_e = 4\pi R_m^2 \rho_{\text{gas}}(R_m) u(R_m)$, where $\rho_{\text{gas}}(R_m)$ is the gas density at $R_m$, which can be estimated from the central gas density and the assumed $\beta$ model, and $u_e(R_m)$ is the bulk gas velocity at $R_m$. Using the stellar mass-loss rates and central gas densities in Table 5, we get $u_e \lesssim 35$ km s$^{-1}$ (see Table 6). The mechanical power of the winds ($\dot{E}_w = M_e u_e^2/2$) is a small fraction of the expected energy injection rate from SNe Ia ($\dot{E}_{\text{SN Ia}}$, see Table 6). As shown in Figure 1, the gas in these galaxies requires an additional heating of approximately 0.3 keV per particle above purely gravitational heating, which is only 5% of the expected SN Ia heating rate. Supernova explosions in low-luminosity early-type galaxies should not experience significant radiative losses due to the lack of cold gas and the long cooling time of the hot gas. Thus, most of the

| Name             | $u_w$ (km s$^{-1}$) | $E_w$ (ergs s$^{-1}$) | $E_{\text{SN Ia}}$ (ergs s$^{-1}$) | $W$ (ergs s$^{-1}$) | $\dot{E}_{\text{SN Ia}}/W$ |
|------------------|--------------------|-----------------------|-----------------------------------|-------------------|-------------------------|
| ESO 0428-G014    | 8.9                | $1.6 \times 10^{36}$  | $4.3 \times 10^{40}$              | ...               | ...                     |
| NGC 821          | ...                | ...                   | $1.0 \times 10^{41}$              | $2.9 \times 10^{40}$ | 3.4                     |
| NGC 1023         | 29                 | $4.0 \times 10^{37}$  | $1.0 \times 10^{41}$              | $2.8 \times 10^{40}$ | 3.6                     |
| NGC 1386         | 4.2                | $3.5 \times 10^{35}$  | $4.1 \times 10^{40}$              | $7.8 \times 10^{39}$ | 5.2                     |
| NGC 1389         | ...                | ...                   | $4.6 \times 10^{40}$              | $5.6 \times 10^{39}$ | 8.2                     |
| NGC 2434         | 6.4                | $1.8 \times 10^{36}$  | $8.7 \times 10^{40}$              | $2.4 \times 10^{40}$ | 3.6                     |
| NGC 2787         | 6.8                | $3.9 \times 10^{35}$  | $1.7 \times 10^{40}$              | $4.5 \times 10^{39}$ | 3.8                     |
| NGC 3115         | 35                 | $6.2 \times 10^{37}$  | $1.0 \times 10^{41}$              | $5.2 \times 10^{40}$ | 1.9                     |
| NGC 3245         | 10                 | $3.5 \times 10^{36}$  | $7.0 \times 10^{40}$              | $2.4 \times 10^{40}$ | 2.9                     |
| NGC 3377         | 11                 | $2.0 \times 10^{36}$  | $3.2 \times 10^{40}$              | $3.8 \times 10^{39}$ | 8.4                     |
| NGC 3379         | 31                 | $2.8 \times 10^{37}$  | $8.6 \times 10^{40}$              | $2.4 \times 10^{40}$ | 3.6                     |
| NGC 3608         | 6.0                | $1.1 \times 10^{36}$  | $6.2 \times 10^{40}$              | $1.7 \times 10^{40}$ | 3.6                     |
| NGC 4251         | ...                | ...                   | $7.8 \times 10^{40}$              | $8.0 \times 10^{39}$ | 9.7                     |
| NGC 4435         | 8.1                | $9.0 \times 10^{35}$  | $2.8 \times 10^{40}$              | $4.9 \times 10^{39}$ | 5.7                     |
| NGC 4459         | 12                 | $6.3 \times 10^{36}$  | $8.9 \times 10^{40}$              | $1.8 \times 10^{40}$ | 4.9                     |
| NGC 4552         | 4.7                | $1.3 \times 10^{36}$  | $1.2 \times 10^{41}$              | $5.9 \times 10^{40}$ | 2.0                     |
| NGC 4697         | 11                 | $6.6 \times 10^{36}$  | $1.1 \times 10^{41}$              | $2.0 \times 10^{40}$ | 5.5                     |
| NGC 5866         | 11                 | $6.4 \times 10^{36}$  | $1.1 \times 10^{41}$              | $1.9 \times 10^{40}$ | 5.8                     |

Notes.—Galaxy name, required wind velocity ($u_w$) to expel the gas from the galaxy at the same rate as the present stellar mass-loss rate, mechanical energy of the wind ($E_w$), SN Ia heating rate ($E_{\text{SN Ia}}$), the required heating rate to remove the stellar mass loss from the gravitational potential of the galaxy ($W$), and the ratio $E_{\text{SN Ia}}/W$. 

TABLE 6
Hot Gas Energetics
The uncertainties in that found in more luminous early-type galaxies. The 4552 has the highest gas content in our sample, it is still less than energetically incapable of driving a wind in NGC 4552. While NGC a galactic wind due to the lack of a confining ambient medium) the more isolated galaxy NGC 3115 (which was able to develop accumulation of a gaseous corona in NGC 4552 is that the ambient gas pressure in the Virgo Cluster was sufficient to suppress the formation of a galactic wind before NGC 4552 experienced significant ram pressure stripping. This would explain the low gas content of the more isolated galaxy NGC 3115 (which was able to develop a galactic wind due to the lack of a confining ambient medium) compared to NGC 4552, even though they have very similar ratios of $E_{\text{SN Ia}}$ to $W$.

7. IMPLICATIONS FOR THE Fe ABUNDANCE OF THE HOT GAS

The gas in these low-luminosity galaxies should have an iron abundance equal to the mass-averaged abundance of the stellar and SN Ia ejecta. Based on our adopted rates given above, the gas should have an abundance 10 times the solar value in Grevesse & Suval (1998), assuming that each SN Ia generates 0.7 $M_\odot$ of Fe. The primary difficulty in determining the gas density and abundance (primarily Fe) of the hot gas in these galaxies is the difficulty in measuring the thermal continuum when there is residual emission from unresolved LMXBs in the diffuse emission. Figure 9 shows the best-fit absorbed power-law plus MEKAL model (assuming solar abundances) to the diffuse emission in NGC 1386, where 45% of the total LMXBs emission is unresolved. Notice that the power-law emission exceeds the thermal continuum at all energies. There is a strong degeneracy between the emission measure and abundance in the fitting process. For example, freezing the abundance at 10 times the solar value and refitting the spectrum simply reduces the flux in the thermal continuum by a factor of 10, while keeping the flux in the Fe L lines and the power-law component essentially the same. Freezing the normalization and index of the power-law model does not reduce the degeneracy. The temperature determination is robust, since it is derived from the centroid of the blended Fe L lines. Since the emission measure is proportional to $n_{e}n_{H}$ and the flux in the Fe L lines is proportional to $n_{e}n_{\text{Fe}}$, it is difficult to accurately determine the gas mass and Fe abundance in these galaxies that is due to the emission from unresolved LMXBs. If the gas in these galaxies has an Fe abundance that is 10 times the solar value, then the central gas densities, gas masses, replenishment times, and cooling times in Table 5 should be reduced by a factor of 3. In addition, the wind velocities in Table 6 should be increased by a factor of 3, and the mechanical power of the winds should be increased by an order of magnitude. Hence, a higher Fe abundance actually strengthens the argument for galactic winds due to the decrease in gas mass and increase in wind velocity. The conclusion that SNe Ia are energetically capable of driving galactic winds in these galaxies is not affected by the Fe abundance of the gas, since this argument mainly depends on the present SN Ia rate, stellar mass-loss rate, and the stellar velocity dispersion in the galaxies.

8. IS AGN HEATING IMPORTANT?

Chandra has detected X-ray cavities and AGN-driven shocks in several early-type galaxies (M84, Finoguenov & Jones 2002; NGC 4636, Jones et al. 2002; Cen A, Kraft et al. 2003). The Chandra image of NGC 4552 shows the presence of two spherical AGN-driven shocks (Machacek et al. 2005). None of the other
galaxies in our sample exhibit any substructure in the diffuse emission, but it is, of course, much easier to detect cavities and shocks in galaxies with significant amounts of hot gas. Seven of the galaxies in our sample were detected in the NRAO VLA Sky Survey (NVSS; Condon et al. 1998). The 1.4 GHz luminosity ($\nu L_\nu$), or upper limit, for the galaxies is given in Table 7. Figure 10 shows that there is no obvious trend between $M_{\text{gas}}/M_*$ and $\nu L_\nu$; however, there is a suggestion that the most radio luminous AGNs reside in galaxies with the highest gas content.

The radio luminosity of an AGN is a poor indicator of its mechanical power. Using Chandra observations of a sample of galaxies and clusters with X-ray cavities, Birzan et al. (2004) found that the ratio of mechanical to radio power varies from 10 in the most radio luminous AGNs, up to $10^6$ in systems with less radio luminous AGNs. Based on these results and a survey of radio-loud galaxies, Best et al. (2006) derived a time-averaged mechanical AGN heating rate of $1.6 \times 10^{41} (M_{\text{bh}}/10^5 M_\odot)^{1.6}$ ergs s$^{-1}$. Using the relation between black hole mass and the absolute red magnitude, $M_R$, found by McLure & Dunlop (2002) of $\log (M_{\text{bh}}/M_\odot) = -0.50 M_R - 2.96$ and an average $R - K$ of 2.5 for the galaxies in our sample, we plot the expected AGN and SN Ia heating rates in Figure 11 against the bolometric luminosity of the hot gas. For comparison, the mechanical power required to generate the observed shocks in NGC 4552 (the upper right-hand point in Fig. 11) is $3 \times 10^{41}$ ergs s$^{-1}$ (Machacek et al. 2005), which is a factor of 2 greater than the rate predicted by Best et al. (2006), but certainly within the uncertainties. Figure 11 indicates that heating by SNe Ia should dominate the energetics of the gas in early-type galaxies with $L_K \lesssim 10^{11} L_{\odot,K}$ and that AGN heating should dominate in more luminous galaxies.

9. DISCUSSION

If heating by SNe Ia is the dominant mechanism for expelling the gas shed by evolving stars from low-luminosity early-type galaxies, it is a puzzle why there is so much scatter in $M_{\text{gas}}/M_*$ and $L_{X,\text{gas}}$ (see Figs. 7 and 11), given that supernova heating is essentially a continuous process. Since the gas masses are computed in different apertures (see Table 5), we checked to see if there is any correlation between $M_{\text{gas}}/M_*$ and aperture size and found none. While the time-averaged SN Ia heating rate shown in Figure 11 exceeds the time-averaged AGN heating rate, except for possibly the most luminous galaxies in our sample, the episodic nature of AGN outbursts could produce times during which mechanical AGN heating exceeds SN Ia heating. Thus, the large observed scatter could be a reflection of recent AGN activity. The sound crossing time within the central 10 kpc in these galaxies is approximately $3 \times 10^7$ yr. If AGN outbursts repeat on a shorter timescale, then the gas will not be able to establish a steady state wind. In the very center of the galaxies, heating by SNe Ia cannot be thought of as a continuous process. For example, within an enclosed stellar mass of $10^6 M_\odot$, there will only be one SN Ia every $3.0 \times 10^7$ yr. During this time, the stars within this region will shed a total of 50 $M_\odot$ of gas. If this gas is converted into mechanical energy by the central black hole with an efficiency of 10%, this will produce $1.0 \times 10^{55}$ ergs of energy at a rate of $1.0 \times 10^{46}$ ergs s$^{-1}$, which is comparable to the SN Ia heating rate of an entire galaxy (see Fig. 10). Thus, it could be that the gas in the very center of the galaxies does not partake in the global SN Ia wind, but periodically accretes into the central black hole.

Environment can also play a significant role in the gas content of early-type galaxies. XMM-Newton and Chandra observations of early-type galaxies in the Coma Cluster have shown that these galaxies can be either underluminous or overluminous in X-rays relative to field galaxies with comparable optical luminosities due to the competing effects of adiabatic compression, ram pressure stripping, and thermal evaporation (Vikhlinin et al. 2001; Finoguenov & Miniati 2004; Hornschemeier et al. 2005). Due to the large distance of the Coma Cluster, these observations were only sensitive to the X-ray properties of luminous early-type galaxies that have massive hydrostatic coronae in regions outside of dense groups or clusters. Low-luminosity field galaxies, however, should have strong winds due to the lack of a confining ambient medium.
NGC 4552 is located in the densest environment of any of the galaxies in our sample and clearly shows the effects of its environment. It is located 72′ (a projected distance of 360 kpc) from the center of the Virgo Cluster, has the highest gas content, and hosts the most radio luminous AGN in our sample. The Chandra image shows that NGC 4552 has a leading cold front and a trailing wake of ram pressure stripped gas (Machacek et al. 2005). Based on the pressure jump across the cold front, Machacek et al. estimated that NGC 4552 is traveling at 1600 km s⁻¹. The average gas density and pressure in NGC 4552 derived from the values in Table 5 are \( n_g = 1.7 \times 10^{-3} \) cm⁻³ and \( P_\text{gas} = 1.9 \times 10^{-3} \) keV cm⁻³. Using the results in Machacek et al., the ram pressure of the Virgo gas at the leading cold front in NGC 4552 is \( P_\text{ram} = 2.2 \times 10^{-3} \) keV cm⁻³, which is greater than the average thermal pressure of the gas, but less than the central pressure of \( P_0 = 3.5 \times 10^{-2} \) keV cm⁻³. These calculations are in good agreement with the fact that some of the outer gas in NGC 452 is being stripped as it falls into the Virgo cluster, but not the central gas. Based on the inferred velocity of NGC 4552, it should have traveled approximately 2 Mpc during the time it has taken to accumulate its present gas mass. The ROSAT all-sky survey data show that the gas in Virgo follows a β = 0.47 profile (Schindler et al. 1999). Assuming the Virgo gas is isothermal and that NGC 4552 has a radial trajectory, the thermal pressure of the Virgo gas surrounding NGC 4552 would have increased by a factor of 20 during this time and the ram pressure by an even greater factor due to the increasing infall velocity. Thus, the ambient pressure during most of this time was sufficient to suppress the formation of a galactic wind, but insufficient to strip the gas from the galaxy. This would have led to a substantial increase in gas mass, which could have triggered the AGN outburst.

10. SUMMARY

We have presented a systematic analysis of Chandra observations of 18 low-luminosity early-type galaxies. Emission from LMXBs is very significant in these galaxies and comprises between 30% and 95% of the total 0.5–2.0 keV emission. We find that the combined X-ray luminosity of LMXBs (resolved plus the power-law component of the unresolved emission) scales approximately linearly with \( L_K \) among the galaxies in our sample with an average \( L_{X,\text{LMXB}}/L_K \) ratio comparable to that found in more luminous early-type galaxies. The gas temperature in these galaxies varies from 0.2 to 0.8 keV and roughly follows the observed trend between gas temperature and stellar velocity dispersion among more luminous early-type galaxies, albeit with significant scatter. The ratio of energy per unit mass in the galaxies to that in the gas, \( \beta_{\text{spec}} \), varies from 0.3 to 1.0, indicating the presence of significant nongravitational heating in most of the galaxies. We do not find any correlation between gas temperature and \( L_{X,\text{gas}} \), unlike more luminous galaxies.

All of the galaxies in our sample are gas-poor, with \( M_{\text{gas}}/M_\star = 0.2–3.0 \times 10^{-3} \), compared to \( M_{\text{gas}}/M_\star = 0.01 \) in more luminous early-type galaxies. The observed gas mass is much less than that expected from the accumulation of stellar mass loss over the lifetime of the galaxies. Based on recent estimates of the stellar mass-loss rate in early-type galaxies, the time required to accumulate the observed gas mass is \( 10^8–10^9 \) yr. Due to the low gas densities, the cooling time of the gas is significantly longer than the replenishment time. Thus, most of the gas shed by evolving stars in these galaxies could not have condensed out of the hot phase and formed stars and must have been expelled from the galaxies in a wind. The only exception to this is the most optically luminous galaxy in our sample, NGC 4552.

Based on recent estimates of the SN Ia rate and mechanical AGN heating rate in early-type galaxies, we find that, on average, heating by Type Ia supernovae should dominate over AGN heating in galaxies with \( L_K \lesssim 10^{11} L_\odot \). Using the stellar mass-loss rate in Atley et al. (2002) and the SN Ia rate in Cappellaro et al. (1999), we find that SNe Ia are energetically capable of driving galactic winds in low-luminosity early-type galaxies even if the present SN Ia rate has been overestimated by a factor of 2 or the stellar mass-loss rate has been underestimated by a factor of 2. We also find that most of the supernova energy must be consumed in lifting the gas out of the gravitational potential well of the galaxies, with little energy converted into thermal or bulk kinetic energy of the gas.

If heating by SNe Ia were the dominant heating mechanism at all times, it would be difficult to account for the large scatter in gas properties among the galaxies in our sample. Even though our calculations show that the time-averaged AGN heating rate is less than the supernova heating rate, the episodic nature of AGN outbursts could produce periods when AGN heating dominates. One possible explanation for the large scatter in gas properties is that galaxies with very little gas at the present time recently experienced a significant AGN outburst that produced a rapid expulsion of the gas. Six of the galaxies in our sample were detected in the NVSS (Condon et al. 1998); however, we do not find any correlations between \( M_{\text{gas}}/M_\star \) and radio power. The lack of a correlation may simply result from the time delay between when the AGN reaches its peak radio power and when the gas is expelled from the galaxy. In fact, the most radio luminous AGN in our sample has the largest gas mass. Another possible source for the observed scatter in gas properties among early-type galaxies is variations in the ambient gas pressure surrounding the galaxies, which would impact their ability to develop galactic winds.

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APPENDIX A

WIND SONIC POINT

Consider a steady, spherical wind driven by energy injected in association with stellar mass loss. Following Mathews & Baker (1971), we assume that stellar mass loss is distributed smoothly and mixes well with the hot ISM, so that we may treat the wind as a single, smooth fluid, with distributed mass injection. The equation of mass conservation is then

\[
\frac{1}{r^2} \frac{d}{dr} \rho vr^2 = \alpha ,
\]  

(A1)
where \( r \) is the radius, \( \rho \) is the gas density, \( v \) is its radial velocity, and \( \alpha (r) \) is the mass injection rate per unit volume due to stellar mass loss. Assuming that the wind extends right to the center of the galaxy, this equation can be integrated to give the mass flow rate through a sphere of radius \( r \),

\[
\dot{M}(r) = 4\pi \rho r^2 = \int_0^r \alpha (r') 4\pi r'^2 \, dr' = \frac{4\pi}{3} \bar{\alpha} r^3 , \tag{A2}
\]

where we have also defined \( \bar{\alpha}(r) \), the mean stellar mass-loss rate per unit volume within \( r \). The momentum equation for the steady wind is

\[
\rho v \frac{dv}{dr} = - \frac{dp}{dr} - \rho g - \alpha v , \tag{A3}
\]

where \( p \) is the gas pressure and \( g(r) \) is the acceleration due to gravity (positive inward). The energy equation may be written

\[
\frac{1}{r^2} \frac{d}{dr} \rho r^2 \left( H + \frac{1}{2} v^2 + \phi \right) = \alpha (\epsilon + \phi) , \tag{A4}
\]

where \( H \) is the specific enthalpy,

\[
H = \gamma p / (\gamma - 1) \rho , \tag{A5}
\]

\( \gamma \) is the ratio of specific heats, \( \phi \) is the gravitational potential and \( \epsilon \) is the total energy per unit mass that is deposited in the flow along with the stellar mass loss, which is due principally to supernova heating, but includes kinetic energy due to random stellar motions, energy injected by planetary nebulae, etc. Following the usual practice, we assume that \( \epsilon \) does not vary throughout the galaxy. Integrating the energy equation gives

\[
\dot{M} \left( H + \frac{1}{2} v^2 + \phi \right) = \int_0^r \alpha (r') \left[ \epsilon + \phi (r') \right] 4\pi r'^2 \, dr' = \dot{M} w , \tag{A6}
\]

which also defines \( w(r) \), a known function of the radius, and we have

\[
w(r) = H + \frac{1}{2} v^2 + \phi \tag{A7}
\]

We ignore the effects of radiative energy loss, which would clearly increase the energy required to drive the wind. These are generally small for the systems considered here.

From equation (A2), the density can be given in terms of the velocity as

\[
\rho = \frac{\bar{\alpha} r}{3w} , \tag{A8}
\]

and from equations (A7) and (A5) we get

\[
\frac{p}{\rho} = \frac{\gamma - 1}{\gamma} \left( w - \frac{1}{2} v^2 - \phi \right) . \tag{A9}
\]

These can be used to eliminate the pressure derivative from the momentum equation (eq. [A3]), giving, after some algebra,

\[
\rho (v^2 - s^2) \frac{dv}{dr} = \frac{\bar{\alpha}}{3} \left[ 2(\gamma - 1) \left( w - \frac{1}{2} v^2 - \phi \right) - \frac{v_K^2}{\alpha} \right] - \alpha \left[ \frac{\gamma + 1}{2} v^2 + (\gamma - 1) \epsilon \right] , \tag{A10}
\]

where the sound speed, \( s \), is given by

\[
s^2 = \frac{\gamma p}{\rho} \tag{A11}
\]

and the Kepler speed, \( v_K \), is defined by \( v_K^2(r) = gr \). Note that in order to obtain this result, we have used \( g = d\phi / dr \) and differentiated the definitions of \( \bar{\alpha} \) (eq. [A2]) and \( w \) (eq. [A6]).

The wind solutions starts with \( v = 0 \) at \( r = 0 \), passes through a sonic point, where \( v = s \), and ends up as a freely expanding, supersonic flow for \( r \to \infty \). At the sonic point \( v^2 = s^2 = (\gamma - 1) \left( w - v^2 / 2 - \phi \right) \) (eqs. [A9] and [A11]), so that

\[
v^2(r_s) = \frac{2(\gamma - 1)}{\gamma + 1} \left[ w(r_s) - \phi (r_s) \right] , \tag{A12}
\]
where \( r_s \) is the radius of the sonic point. In order for the solution to pass through the sonic point, the right-hand side of equation (A10) must vanish there. After using equation (A12) to eliminate the velocity, the resulting condition may be written

\[
\left[ \frac{4\pi(r_s)}{3(\gamma + 1)} - \alpha(r_s) \right] [w(r_s) - \phi(r_s)] = \alpha(r_s) \epsilon + \frac{\pi \nu_k^2}{3(\gamma - 1)}. \tag{A13}
\]

The terms on the right of this equation are both positive and, since \( H + v^2/2 > 0 \), equation (A7) requires \( w - \phi > 0 \), too. Thus,

\[
\frac{4\pi(r_s)}{3(\gamma + 1)} > \alpha(r_s). \tag{A14}
\]

Defining

\[
\bar{\phi}(r) = \int_0^r \frac{\alpha(r') \phi(r') r'^2 dr'}{\int_0^r \alpha(r') r'^2 dr'}, \tag{A15}
\]

from the definition of \( w \) (eq. [A6]), we have \( w(r) = \epsilon + \bar{\phi}(r) \). Using this in equation (A13) and solving for \( \epsilon \) gives

\[
\epsilon \left[ \frac{4\pi(r_s)}{3(\gamma + 1)} - 2\alpha(r_s) \right] = \left[ \frac{4\pi(r_s)}{3(\gamma + 1)} - \alpha(r_s) \right] [\phi(r_s) - \bar{\phi}(r_s)] + \frac{\pi \nu_k^2(r_s)}{3(\gamma - 1) r_k^2(r_s)}. \tag{A16}
\]

Since \( \phi \) is an increasing function of the radius, \( \phi(r_s) - \bar{\phi}(r_s) > 0 \), and we showed above (eq. [A14]) that the factor multiplying it is positive. Thus, we must also have

\[
\frac{2\pi(r_s)}{3(\gamma + 1)} > \alpha(r_s). \tag{A17}
\]

Under the usual assumption that \( \alpha \) is proportional to the stellar density, this condition requires the mean density to be substantially greater than the local density at the sonic point. Thus, the sonic point must occur well outside the dense stellar core of a typical galaxy. We can now rewrite the result for \( \epsilon \) as

\[
\epsilon = \left\{ \phi - \bar{\phi} \left( \frac{(\gamma + 1)\nu_k^2}{4(\gamma - 1)} \right) + \alpha \left[ \phi - \bar{\phi} \left( \frac{(\gamma + 1)\nu_k^2}{2(\gamma - 1)} \right) \right] \right\} \left[ \frac{4\pi}{3(\gamma + 1)} - 2\alpha \right] \bigg|_{r=r_s}, \tag{A18}
\]

knowing that all of the factors in the term multiplied by \( \alpha \) are positive. For a galaxy model with specified potential and stellar mass-loss rate, \( \alpha \), this expression enables us to determine the specific energy injection rate, \( \epsilon \), from the location of the sonic point. Alternatively, if the energy injection rate is known, this equation may be solved to find the location of the sonic point. In particular, in the limit of large energy input, the sonic point approaches the radius that makes the denominator of the second term vanish, i.e., that makes inequality (A17) an identity.

For the remainder of this discussion, we assume that the stellar mass-loss rate is proportional to the stellar density. Inside a galaxy, the right-hand side of the expression for \( \epsilon \) is generally a decreasing function of the sonic radius, \( r_s \), so that the energy input required to drive a wind is minimized when the sonic point occurs at large \( r \). If the stellar density falls rapidly to zero at the edge of the galaxy, \( \alpha \) falls to zero quickly, while the other terms in this expression are continuous. Thus, there is a rapid reduction in the energy required to drive the wind as the sonic point moves across the outer edge of the galaxy. As a result, the sonic point occurs close to the edge of the stellar distribution for a range of values of \( \epsilon \).

Beyond the edge of the stars \( \alpha = 0 \) so that \( \bar{\phi}(r) \) is constant (from definition [A15]). The remaining variable terms in equation (A18), \( \phi(r) + (\gamma + 1)\nu_k^2(r)/(4(\gamma - 1)) \), may increase or decrease with radius, depending on the value of \( \gamma \) and the distribution of the gravitating matter (which may extend beyond the stars). For \( \gamma = 5/3 \), these terms reduce to \( \phi(r) + \nu_k^2(r) \), which is a nondecreasing function of \( r \) [since \( \nu_k^2(r) = GM(r)/r \)], where \( M(r) \) is the gravitating mass within \( r \), so that the global minimum of expression (A18) occurs at a value of \( r_s \) close to, or immediately outside the edge of, the stellar distribution. However, the local condition for the sonic point (eq. [A18]) does not guarantee that the wind solution can be extended to infinity. Beyond the edge of the stars, \( w(r) \) is also constant, and it is evident from equation (A7) that it is necessary for \( w = \epsilon + \bar{\phi} \geq 0 \) for the wind solution to extend to \( r = \infty \), an essential requirement for a steady wind. Thus, the global minimum value of \( \epsilon \) required for a wind when \( \gamma = 5/3 \) is

\[
\epsilon_{\text{min}} = -\bar{\phi}(\infty). \tag{A19}
\]

Similar considerations apply for \( \gamma < 5/3 \), except that the energy requirement may now be minimized for \( r_s \to \infty \) in equation (A18). Thus, we arrive at the same global value for \( \epsilon_{\text{min}} \). Note that, for \( \gamma = 5/3 \), the wind solution with \( w = 0 \) attains a constant Mach number beyond the edge of the gravitating matter, rather than having the Mach number approach infinity. For \( \gamma < 5/3 \), when the energy requirement is minimized for \( r_s \to \infty \), the flow would be subsonic everywhere. In that case, the effect of a disturbance at finite \( r \) is felt throughout the wind flow. In either case, the wind solution is fragile. This is not surprising for a wind driven with the absolute minimum energy. It emphasizes that the minimum energy requirement is just that. In reality, greater energy is required to sustain a wind.
To evaluate $\phi$, we assume that the gravitational potential has the Navarro-Frenk-White (NFW) form,

$$\phi(r) = -4\pi G\rho_0 a^2 \left[ \frac{\ln (1 + r/a)}{r/a} - \frac{1}{1 + c} \right], \quad \text{for } r < ac,$$

(A20)

where $a$ is the scale length, $\rho_0$ is the scale density, and $c$ is the concentration parameter. The stars, hence the mass injection rate, are assumed to have the King model distribution

$$\alpha(r) = \frac{\alpha_0}{(1 + r^2/b^2)^{1/2}},$$

(A21)

where $b$ is the core radius. Using definition (A15), we then get

$$\bar{\phi}(r) = -4\pi G\rho_0 a^2 \left[ -\frac{1}{1 + c} + \frac{1}{\frac{\ln (1 + \beta y)}{\beta \sqrt{1 + y^2}} + \frac{1}{\frac{1}{\sqrt{1 + \beta^2}} \ln (1 + \beta y + \beta \sqrt{1 + y^2} - \sqrt{1 + \beta^2})(1 + \beta + \sqrt{1 + \beta^2})} \right.$$

$$\left. - \frac{\ln (1 + \beta y)}{\beta \sqrt{1 + y^2}} + \frac{1}{\frac{1}{\sqrt{1 + \beta^2}} \ln (1 + \beta y + \beta \sqrt{1 + y^2} + \sqrt{1 + \beta^2})(1 + \beta - \sqrt{1 + \beta^2})} \right],$$

(A22)

where $\beta = b/a$, $y = r_c/b$, and the stellar distribution is cut off at $r_c$. The normalizing factor for the NFW potential, $4\pi G\rho_0 a^2$, was determined from the assumption that the maximum rotation speed is related to the line-of-sight velocity dispersion by $v_{K,\text{max}}^2 = 2\sigma^2$, giving

$$4\pi G\rho_0 a^2 = \lambda \sigma^2,$$

(A23)

with $\lambda \approx 9.25$. Equating the mean density of the halo to $\chi$ times the critical density then gives the scale length,

$$a = \frac{\sigma}{H_0} \sqrt{\frac{2\chi}{\lambda} [\ln (1 + c) - c/(1 + c)]},$$

(A24)

where $H_0$ is the Hubble constant. Parameters for the King model are set to match photometric properties of the galaxies.

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