CHANDRA DETECTION OF MASSIVE BLACK HOLES IN GALACTIC COOLING FLOWS

FABRIZIO BRIHENTI and WILLIAM G. MATHWS

University of California Observatories/Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, Santa Cruz, CA 95064; mathews@lick.ucsc.edu

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ABSTRACT

Anticipating forthcoming Chandra X-ray observations, we describe the continuation of interstellar cooling flows deep into the cores of elliptical galaxies. Interstellar gas heated to $T > 1$ keV in the potential of massive black holes ($r \leq 50$ pc) should be visible unless thermal heating is diluted by nonthermal pressure. Since our flows are subsonic near the massive black holes, distributed cooling continues within ~300 pc. Dark, low-mass stars formed in this region may be responsible for some of the mass attributed to central black holes.

Subject headings: black hole physics — cooling flows — galaxies: elliptical and lenticular, cD — galaxies: ISM

1. INTRODUCTION

Considerable observational evidence now exists for supermassive black holes (SMBHs) in the centers of giant elliptical galaxies. These mass concentrations, long suspected to be the origin of nonthermal energy in active galaxies, are now thought to be responsible for large gas or stellar velocities in galactic cores (Ho 1999). We discuss here the interaction of SMBHs with hot ($T \sim 10^7$ K) interstellar gas. The local compression and heating of interstellar gas in the SMBH potential can be detected with the Chandra X-ray telescope. Indeed, the inflow of interstellar gas may explain the growth of SMBHs in galactic cores. However, X-ray detection of SMBHs may not be possible if the nonthermal interstellar pressure is comparable to the pressure of hot thermal gas.

As we were completing this work, a similar study of the SMBH-gas interaction by Quataert & Narayan (1999, hereafter QN) appeared on the astro-ph preprint server. While some of the conclusions of QN are supported by our flow calculations, our results are qualitatively different in a number of important ways. The steady state flows considered by QN are constrained to pass through a sonic point, becoming supersonic near the SMBH. By comparison, our (nonsteady) computational gas flows near the SMBH adapt naturally to the interstellar cooling flow in the surrounding galaxy and, as a result, our flow velocity is fully subsonic near the SMBH. We also consider several additional physical effects not discussed by QN: time-dependent ejection of mass by evolving stars, heating by Type Ia supernovae, nonthermal pressure, and the gravitational field of (dark) cooled interstellar gas which in some observations may be confused with the mass of the SMBH.

Although we use observations of the bright Virgo elliptical galaxy NGC 4472 as a guide for our models, we do not seek here a set of parameters for an optimal fit to this galaxy. Instead, our objective is to illustrate some of the physical effects that must be considered in interpreting X-ray observations of the cores of bright elliptical galaxies with the Chandra telescope. At a distance $d = 17$ Mpc appropriate for NGC 4472, Chandra’s resolution (~0.5') is ~40 pc.

2. CONSTRUCTING MODELS

The computational procedure we follow here is identical to that described in our recent papers (e.g., Brighenti & Mathews 1999a). With NGC 4472 in mind, we construct a galaxy in a cosmological environment beginning with an overdensity perturbation designed to form a galaxy group. Stars of total mass $M_\odot = 7.26 \times 10^{11}$ (appropriate to NGC 4472 with $M/L_h = 9.2$; van der Marel 1991) are formed from the baryons at an early time ($t_\odot = 1$ Gyr) and later ($t_\odot = 2$ Gyr) merge into a de Vaucouleurs profile. An evolving Navarro-Frenk-White dark halo develops around the galaxy over time, accompanied by secondary infall, although within an effective radius ($r_\odot = 8.57$ kpc for NGC 4472) stellar mass loss provides at least half of the hot interstellar gas. A cooling flow develops in the hot interstellar gas at early times and slowly evolves toward its present configuration at $t_\odot = 13$ Gyr. Over time a large mass of interstellar gas cools and "drops out" in NGC 4472, $M_{\odot} \approx t_\odot L_\odot/(5KT/2\mu m)$, $\approx 4 \times 10^{10} M_\odot$, where $L_\odot$ is the X-ray luminosity. Since this mass exceeds the mass observed in the central black hole in NGC 4472, $\approx 2.6 \times 10^8 M_\odot$ (Mogor et al. 1998), interstellar gas must cool in localized thermal instabilities distributed throughout an extended galactic volume within $r_\odot$. This distributed interstellar cooling is modeled by adding a sink term to the equation of continuity: $-q(r)p/\dot{r}_\odot \propto \rho^\gamma$, where $\dot{r}_\odot = 5m_\odot K/2\mu m\Delta$ is the time for gas to cool locally by radiative losses at constant pressure (e.g., Sarazin & Aske 1989). We find that taking $q = 1$ provides a satisfactory global interstellar flow solution for NGC 4472 that matches currently observed density, temperature, and metallicity profiles reasonably well (Brighenti & Mathews 1999a, 1999b); we adopt $q = 1$ here.

To resolve the small-scale flow near the SMBH, we refine our logarithmic spatial grid in the galactic core to an innermost zone of radius 12 pc. Interstellar gas is influenced by the black hole within a radius $r_\odot \sim GM_\odot/c^2 \approx 48(M/10^9 M_\odot)(c^2/300$ km s$^{-1})^{-2}$ pc; $c$ is the sound speed in the hot gas. We ignore the effects of galactic rotation. Although the mass-losing stellar systems in large elliptical galaxies like NGC 4472 are slowly rotating, their X-ray images do not indicate the flattening expected if the hot interstellar gas shared this rotation (Brighenti & Mathews 1996). Evidently, efficient cooling dropout or turbulent viscosity removes angular momentum from the hot gas.

3. A "STANDARD" MODEL

Figure 1 shows the interstellar density, temperature, and $(ROSAT)$ X-ray surface brightness evolved to the present time, $t_\odot = 13$ Gyr. During the evolution, new gas and energy
are supplied from stellar sources: (1) the specific stellar mass-loss rate is \( \alpha_s(t) = 4.7 \times 10^{-20} \frac{t(t_m - t)}{t_m} \) s\(^{-1}\) and (2) gas is heated by Type Ia supernovae at a rate \( \dot{S}_\text{Nu}(t) = S\dot{N}_\text{u}(t) \), where \( S\dot{N}_\text{u}(t) = 0.03 \) Type Ia supernovae per 100 yr per \( 10^{40} L_{\odot} \) (Cappellaro et al. 1997). The interstellar gas temperature is nearly virial, \( T \approx 10^7 \) K. The stellar density has a de Vaucouleurs profile but flattens to \( \rho_c \propto r^{-6/7} \) within a “break” radius \( r_b = 206 \) pc (Faber et al. 1997).

The dashed lines in Figure 1 refer to solutions without central black hole, and the solid lines refer to solutions with a central black hole of mass \( 2.0 \times 10^9 M_\odot \) introduced at \( t_*= 2 \) Gyr. In this \( q = 1 \) solution, an additional \( 0.7 \times 10^9 M_\odot \) flows inside \( r = 12 \) pc by \( t_* = 13 \) Gyr, increasing the central dark mass to \( 2.7 \times 10^9 M_\odot \). The gas density (with a SMBH) varies approximately as \( n \propto r^{-3/4} \) over most of the flow. For \( r \lesssim 300 \text{ pc} \), the computed density appears to exceed the innermost observations; we discuss this apparent discrepancy in more detail below. The thin curves in Figure 1 for \( T(r) \) refer to the background flow; thick curves show the projected temperature including emission from distributed cooling regions and correspond to the temperature observed. For constant \( q \), cooling dropout is important throughout the flow and extends to the region adjacent to the SMBH. The gas temperature rises dramatically within about 50 pc from the SMBH—detection of this thermal peak by Chandra would provide additional evidence for a SMBH. This temperature spike should be visible even when viewed with Chandra in projection against the entire cooling flow: the mean projected thermal temperatures within apertures of \( R = 50, 100, \) and 500 pc are 2.95, 2.70, and 2.00 \( \times 10^7 \) K (with a SMBH) and 1.04, 1.05, and 1.09 \( \times 10^7 \) K (without a SMBH), respectively.

The top panel in Figure 2 shows the current flow velocity \( v(r) \) and the local mass flow \( \dot{M}(r) = 4\pi r^2 \rho v \). A small influence due to the SMBH potential at times \( t \approx t_* \) can be seen in the distant flow \( r \gtrsim 30 \) kpc, where the flow time \( t_f = rv \gtrsim t_* - t_* \). Overall, the flow is very subsonic even in the vicinity of the SMBH where \( c_s \approx 300 \text{ km s}^{-1} \). This occurs for two reasons: (1) the high pressure in the central thermal spike (e.g., Holzer & Axford 1970), enhanced by the SMBH, and (2) mass drop-out, which tends to make subsonic flow even slower. By contrast, the solutions of QN [with \( \alpha_s(t) = 0 \)] are constrained to pass through a sonic transition, causing the gas to accelerate through the thermal spike. (Without mass dropout [\( q = 0 \)], we also find a transition to supersonic flow at \( \sim 60 \) pc.) Our calculations shown in Figures 1 and 2 were done with the bound-

![Figure 1](image1.png)

**Fig. 1.**—Structure of the standard cooling flow solution, shown both with (solid line) and without (dashed line) a supermassive black hole of mass \( M_{\bullet} = 2 \times 10^9 M_\odot \). Top: Radial variation of apparent gas density including cooling regions. Middle: Variation of gas temperature with galactic radius in the background flow (thin lines) and with projected radius including emission from cooling regions (thick lines). Bottom: Variation of gas temperature with galactic radius in the background flow (thin lines) and with projected radius including emission from cooling regions (thick lines). Filled circles are Einstein HRI observations (Trinchieri et al. 1986), and open circles are ROSAT HRI and PSPC observations (Irwin & Sarazin 1996).

![Figure 2](image2.png)

**Fig. 2.**—Additional properties of the standard cooling flow solution shown in Fig. 1. Top: Radial variation of the flow velocity (thin lines) and mass flow rate (thick lines). Solutions with and without a supermassive black hole are shown as solid and dashed curves, respectively. Bottom: Gravitational acceleration due to a SMBH (long dashed line), old stellar population (thick dotted line), the dark halo (solid line), and the interstellar gas (dot-dashed line).
ary condition $v(r = 0) = 0$; accumulated gas in the central zone cools there. To encourage the onset of supersonic flow near the SMBH, we repeated the calculation allowing the gas to flow freely through a small radius (as small as $r = 1$ pc with a very high resolution grid) and found that the flow was essentially unchanged from that shown in the figures. The fully subsonic character of our solutions is therefore quite robust and independent of our boundary condition at $r = 0$. (In principle, our flow should become supersonic very near the Schwarzschild radius $r_s \approx 10^4$ pc, but this cannot be resolved by our spatial grid and it is likely that additional physical effects become important as $r$ approaches $r_s$.)

Because our flow in the thermal spike near the SMBH is subsonic, the cooling time $\tau_\text{cool}$ remains comparable to the flow time $t_\text{flow} = r/h$ throughout this region and cooling dropout continues unabated at small radii, unlike the QN solutions. This concentrated mass dropout has two important astrophysical consequences: (1) the mass deposited by interstellar cooling near the SMBH may be comparable to that of the SMBH itself, and (2) the rate at which mass flows into the SMBH at the origin is significantly reduced (by about ~10) below the QN solutions.

The mass of cooled interstellar gas in our model with a SMBH in Figure 2 is large: $M_\text{H}(r) = 2.3 \times 10^5$, $3.5 \times 10^5$, and $8.0 \times 10^5 M_\odot$ within $r = 50, 100, 300$ pc, respectively. These masses are comparable to SMBH masses found by Magorrian et al. (1998), and they occur within the small region ($\leq 4''$ or 330 pc for NGC 4472) in which stellar velocities are enhanced by the SMBH. The gravitational acceleration due to the SMBH, the dropout mass, old stars, and dark halo are also shown in Figure 2; note that the dropout mass dominates gravitational forces at $r \approx 200$ pc. In view of the possibility of contamination with dropout mass, the true mass of the central SMBH may be lower than those quoted by Magorrian et al. (1998). These considerations depend on our assumption that interstellar mass dropout continues to the smallest galactic radii; at the present time, there is no reason to question this assumption.

In Figure 3 we illustrate a solution identical to that in Figure 2 but with an initial SMBH mass of only $M_{\text{BH}} = 1 \times 10^5 M_\odot$; the visibility of the thermal spike is noticeably reduced.

### 4. "NONSTANDARD" MODELS

We now return to the apparent disagreement in Figure 1 between our models and the innermost observed $\Sigma_X(R)$ and deprojected electron density.

Can the apparent flattening of observed $\Sigma_X(R)$ at small radii be due to absorption of X-rays by cold gas in $r \approx 300$ pc? The H ii gas that produces optical emission lines in NGC 4472 (Macchetto et al. 1996) cannot account for the X-ray absorption since H ii emission from such H ii clouds in pressure equilibrium would be $\approx 1000$ times more intense than $L_\text{Hii}$ observed in this region of NGC 4472. Suppose instead that the absorbing gas is cold H i or H2 and is distributed in a uniform disk extending to $r \approx 300$ pc oriented perpendicular to the line of sight. If the disk column density is $N \approx 10^{20}$ cm$^{-2}$ [i.e., $\tau(1 \text{ keV}) \approx 1$], the total disk mass, $\approx 2 \times 10^6 M_\odot$, would be consistent with upper limits on observed H i and H2 in NGC 4472, $M_{\text{cold}} \leq 10^5 M_\odot$ (Bregman, Roberts, & Giovanelli 1988; Braine, Henkel, & Wiklind 1997). However, in pressure equilibrium with the hot cooling flow gas, the density of such cold gas (at $T \approx 15$ K; Mathews & Brighenti 1999) is very high, $n_{\text{cold}} \approx 6 \times 10^3$ cm$^{-3}$, and the disk thickness is incredibly small, $h \approx Nn_{\text{cold}} \approx 6 \times 10^{-4}$ pc. Whether such a peculiar and fragile disk could exist in NGC 4472 (and other Virgo elliptical galaxies with similar cores; Brighenti & Mathews 1997) seems unlikely. However, optical line emission from the surface of the disk ionized by stellar UV (Mathews & Brighenti 1999) would exceed observed limits. For H ii gas at $T \approx 10^4$ K, the pressure equilibrium density at $r_\text{f} = 300$ pc is $n_{H\text{ii}} \approx 850$ cm$^{-3}$ and the Stromgren radius is $R_{\text{Stromgren}} \approx 10^6$ cm. The total H β energy emitted by the disk, $L_{\text{Hβ},d} \approx 2 \pi r_\text{f}^2 n_{\text{H\text{ii}}}^2 \tau_{\text{H\text{ii}}} \approx 4 \times 10^{39}$ ergs s$^{-1}$, is ~6 times larger than the total H β luminosity from NGC 4472, $L_{\text{Hβ}} \approx 7 \times 2 \times 10^{39}$ ergs s$^{-1}$. This inconsistency cannot be removed with other geometrical arrangements of the absorbing cold gas within 300 pc, so the apparent inner flattening in Figure 1 is probably not due to cold gas absorption.

We have also explored the possibility that the $\Sigma_X(R)$ observations shown in Figure 1 were centrally flattened by the 4" half-power Gaussian point-spread function (Giacconi et al. 1979) of the Einstein HRI. However, such a convolution of our computed $\Sigma_X(R)$ cannot duplicate the core observed in NGC 4472. X-ray cores in NGC 4472, NGC 4636, and NGC 4649 (Trinchieri, Fabbiano, & Canizares 1986) are not artifacts of limited observational resolution.

These difficulties led us to explore two additional "nonstandard" models for NGC 4472: flows (1) with extreme mass dropout inside 300 pc or (2) with additional nonthermal pressure in this same region.
It is often claimed that mass dropout reduces the X-ray surface brightness in the central regions of cooling flows, but this is not true in general. For flows in which most of the gas in the central region has advected inward from large radii, cooling dropout at large radii can reduce the amount of gas and associated emission $\Sigma_n(R)$ in the central core. However, this does not apply to galactic cooling flows in which much of the gas in the central flow originates from stars within or near this region. In addition, the X-ray emissivity and $\Sigma_n(R)$ are locally enhanced at (denser) cooling sites where mass dropout occurs. To illustrate the futility of lowering the central $\Sigma_n(R)$ in NGC 4472 with increased local cooling, we show in Figure 3 density and temperature profiles for the standard flow (at $t_e$ and with a SMBH) but with a cooling dropout that truncates the background flow density: $q(r) = e^{n(r)/n_0}$ with $n_0 = 0.006 \text{ cm}^{-3}$. The thermal spike around the SMBH is still present in this solution, but the apparent $n(r)$ [and $\Sigma_n(R)$] within several 100 pc is only slightly reduced. The mean projected temperature within 100 pc is $T(R < 100) = 1.9 \times 10^7 \text{ K}$.

Finally, we consider cooling flow models in which $n(r)$ and $\Sigma_n(R)$ in the inner flow are lowered by an additional nonthermal pressure due to relativistic particles or magnetic fields, as suggested by radio emission observed in most elliptical cores. To explore this possibility, we show in Figure 3 the standard flow (at $t_e = 13 \text{ Gyr}$ with a SMBH) in which an additional pressure is introduced in the galactic core: $P_n = P(1 + 5e^{-n/2})$, where $P$ is the thermal gas pressure. The density (and $\Sigma_n$) in the cooling flow within 300 pc are reduced by this additional pressure, and parameters for $P_n(r)$ can be adjusted in an ad hoc fashion to achieve a more perfect fit with the observations. However, the apparent temperature of the thermal gas is dramatically lowered since the external flow is now supported mostly by nonthermal pressure. The projected apparent temperature within $R = 100 \text{ pc}$ is only $T = 0.40 \times 10^7 \text{ K}$, assuming this gas is not heated by collective interactions with the relativistic gas. The thermal spike near the SMBH is now eliminated.

5. FINAL REMARKS AND CONCLUSIONS

In this study, we have examined central cooling flows in a luminous elliptical galaxy similar to NGC 4472. We have emphasized the evolution of quiescent flows that arise naturally from gas and energy supplied by galactic stars and by secondary infall in the outer regions. We have not explored possible transient interactions between the cooling flow and an intermittently active galactic core (e.g., Ciotti & Ostriker 1997). Our objective here has been to anticipate some of the interpretive issues that may arise when Chandra observations become available.

Our main conclusions are as follows:

1. Some dark matter currently attributed to the central SMBH may be due to a population of nonluminous stars created from cooled interstellar gas having a bottom-heavy initial mass function (IMF). In the standard cooling flow for NGC 4472 with a SMBH, neutral clouds become gravitationally unstable (and truncate the IMF) at masses $n_e = 0.2$, 0.3, and 0.8 $M_\odot$ at $r = 50$, 100, and 300 pc, respectively (Mathews & Brighenti 1999). Such dark stars, possibly having approximately radial orbits, can also produce a radial variation in the global baryonic MIL.

2. A successful observation of a high-temperature peak in $r \leq 50 \text{ pc}$ by Chandra in a nearby bright elliptical galaxy would provide additional strong evidence for the existence of SMBHs. However, if additional nonthermal pressure is present in elliptical cores, the SMBH thermal peak may no longer be discernible.

3. Our central flows ($r \leq 300 \text{ pc}$) differ from the Bondi-type transonic flow described by QN since we do not insist on a sonic transition. The mass-flow rate into the SMBH is considerably reduced in our models.

4. As long as our standard cooling flow assumptions hold, we expect the gas density to rise steadily toward the SMBH approximately as $n \propto r^{-5/4}$. But current observations suggest that such a gas density peak is not present. About half of the gas within 300 pc in NGC 4472 is supplied by mass loss from stars in this region. In our standard cooling flow model, we have assumed that all stellar ejecta rapidly enters the hot interstellar phase (in $\approx 10^4 \text{ yr}$). It has occasionally been suggested (e.g., Thomas 1986) that stellar ejecta cools before entering the hot gas, effectively reducing $\alpha_e$. However, we find that the central peak in $n(r)$ and $\Sigma_n(R)$ persists even if the stellar mass-loss rate $\alpha_e$ is reduced at small $r$. Moreover, dynamical arguments and gas temperature and metallicity gradients observed at larger radii ($r \approx 3e$) strongly indicate that cooler, enriched stellar ejecta is conductively melting into the hot phase.

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