Chandra, GLAST, and the Galactic Center

Eliot Quataert[1] and Andrei Gruzinov
Institute for Advanced Study, School of Natural Sciences, Einstein Drive, Princeton, NJ 08540; eliot@ias.edu, andrei@ias.edu

ABSTRACT

Two-temperature spherical accretion flows produce $\approx 100 \text{ Mev}$ gamma-rays from the decay of neutral pions created in proton-proton collisions close to the black hole; they also produce $\sim 10 \text{ keV}$ X-rays by bremsstrahlung emission at large radii. The gamma-ray to X-ray luminosity ratio is nearly independent of black hole mass and accretion rate. It does depend sensitively on the radial density profile of the accretion flow through the parameter $a$, where $n \propto r^{-a}$. For the canonical Bondi value of $a = 3/2$, the gamma-ray to X-ray luminosity ratio is $\approx 30$. We interpret a recent Chandra detection coincident with the massive black hole at the Galactic Center as being thermal bremsstrahlung emission from the accretion flow. With this normalization, the expected gamma-ray luminosity is $\approx 10^{35} \text{ ergs s}^{-1}$ if $a = 3/2$. This is nearly two orders of magnitude above the detection threshold of the GLAST telescope. For $a \approx 1/2$, however, (a value suggested by recent theoretical arguments), the expected gamma-ray luminosity is only $\approx 10^{29} \text{ ergs s}^{-1}$; GLAST should therefore provide an important probe of the true accretion rate and radial density profile of the accretion flow onto Sgr A*.

Subject Headings: accretion, accretion disks — Galaxy: center — gamma rays: theory

1. Introduction

In roughly spherical accretion flows, be it Bondi (1952) or advection-dominated accretion flows (ADAFs; Rees et al. 1982, Narayan & Yi 1994), the protons have temperatures comparable to their gravitational potential energy. Close to the black hole, a significant number of protons are energetic enough to exceed the threshold for the production of pions in proton-proton collisions. Neutral pions quickly decay to produce gamma-rays. It has long been recognized that this is a plausible source of gamma-ray emission from spherical accretion flows (Shvartsman 1971; Dahlbacka, Chapline, & Weaver 1974; Colpi, Maraschi, & Treves 1986; Mahadevan, Narayan, & Krolik 1997).

In this paper we place the expected gamma-ray emission from spherical accretion flows on firmer observational ground by relating it to the more readily observable x-ray emission produced by thermal bremsstrahlung. A simple and relatively universal relationship between the two fluxes

---

[1] Chandra Fellow
exists because both are produced by two-body processes. This is discussed in the next section (§2). We then apply these considerations to Sgr A*, the supermassive black hole at the center of our galaxy (§3). In §4 we briefly summarize our results.

2. The Gamma-ray to X-ray Luminosity Ratio

We first give a simple calculation of the gamma-ray to x-ray luminosity ratio assuming self-similar scalings for the density and temperature of the flow and a thermal distribution of protons. We then discuss the uncertainties introduced by these approximations.

We take the temperature and number density of the flow to be

\[ \theta_p = \theta_0 r^{-1} \quad \text{and} \quad n = n_0 r^{-a}, \]

(1)

where \( \theta_p = kT_p/m_p c^2 \) is the dimensionless proton temperature, \( r \) is the radius in the flow in units of the Schwarzschild radius \( (R_S) \), and \( n_0 \) is the normalization of the density, which depends on, e.g., the black hole mass, the accretion rate, and the viscosity parameter \( \alpha \). For \( \theta_0 = 0.15 \), the proton temperature profile is that of non-relativistic Bondi accretion with an adiabatic index of \( \gamma = 5/3 \); comparable maximal temperatures and identical radial scalings occur in relativistic Bondi accretion (Shapiro 1973) and ADAFs (Narayan & Yi 1995). The electron temperature profile is rather uncertain; fortunately we will only need the electron temperature at large radii, \( r > \sim 10^3 \), where the flow is well approximated as one temperature. In equation (1) we allow the radial density profile to differ from the canonical Bondi value of \( a = 3/2 \); recent work on ADAFs has shown that much smaller values, e.g., \( a = 1/2 \), may be appropriate (see §2.2).

The number of \( \approx 100 \) Mev gamma-rays produced per second and per cm\(^3\) is given by \( n^2 R(\theta_p) \), where \( R(\theta_p) \) is the reaction coefficient for thermal protons of temperature \( \theta_p \). At \( \theta_p \approx 0.15 \), \( R(\theta_p) \) can be approximated by \( R(\theta_p) \approx R_0 (\theta_p/0.15)^3 \), where \( R_0 \approx 2 \times 10^{-17} \) cm\(^3\) s\(^{-1}\) (see Fig. 3 of Dermer 1986); for \( \theta_p \approx 0.05 \), \( R(\theta_p) \) decreases much more rapidly than \( \propto \theta_p^3 \). Integrating over the flow, the photon luminosity in \( \approx 100 \) Mev gamma-rays is

\[ N_\gamma = 4\pi R_S^3 n_0^2 \int_1^\infty \left( \frac{dr}{r} \right) R(\theta) r^{3-2a} \approx \frac{2\pi}{a} R_S^3 n_0^2 R_0. \]

The number of x-rays of frequency \( \nu \) produced per second and per cm\(^3\) is given by \( n^2 R_\nu(\theta_e) \), where \( R_\nu(\theta_e) \approx \beta \theta_e^{-1/2} \exp[-h\nu/kT_e] \) and \( \beta \approx 1.3 \times 10^{-16} \) cm\(^3\) s\(^{-1}\) (e.g., Rybicki & Lightman 1979).

\(^2\)Relativistic corrections are small.
Integrating over the flow, the photon luminosity in x-rays of frequency $\nu$ is

$$N_X = 4\pi R_S^3 n_0^2 \beta \int_1^{\infty} \left( \frac{dr}{r} \right) r^{3-2a} \theta_r^{-1/2} \exp[-h\nu/kT_e].$$  \hspace{1cm} (3)

Equation (3) shows that at a frequency $\nu$ the x-ray emission is dominated by the largest radius which satisfies $kT_e \gtrsim h\nu$. This is because $r^{3-n^2}T_e^{-1/2}$ increases with increasing radius. We focus on x-ray emission at $\sim 10$ keV which is dominated by emission from $r \sim 10^3 - 10^4$. At these radii the flow is quite accurately approximated as one-temperature so we can substitute $T_e = T_p$ ($\theta_r = m_p^2 \theta_p/m_e$) into equation (3) and perform the integral

$$N_X \approx \frac{4\pi R_S^3 n_0^2 \beta^2 \theta_r^{-1/2}}{3.5 - 2a} r^{3.5-2a},$$  \hspace{1cm} (4)

where $r_\nu = \theta_0/\theta_r$, $\theta_r = h\nu/m_p c^2$, and $\beta' = \beta(m_e/m_p)^{1/2} \approx 3 \times 10^{-18} \text{ cm}^3 \text{ s}^{-1}$.

Combining equations (2) and (4), the ratio of the gamma-ray luminosity at energy $E_\gamma \approx 100$ MeV to the x-ray luminosity at energy $E_X$ is given by

$$\frac{L_\gamma}{L_X} \approx \left( \frac{E_\gamma}{E_X} \right) \left( \frac{3.5 - 2a}{a} \right) r^{2a-3.5} \approx 30 \left( \frac{10 \text{ keV}}{E_X} \right)^{1/2},$$  \hspace{1cm} (5)

where the last approximation takes $a = 3/2$.

Equation (5) shows that, for the self-similar analysis of this subsection, the gamma-ray to x-ray luminosity ratio of the flow depends only on the radial density profile. Since both pion decay and bremsstrahlung involve two-body processes the luminosity ratio from any spherical shell depends only on the local temperature(s). The radial density profile enters because pions are only produced in interesting numbers very close to the black hole while the x-ray luminosity primarily originates from rather large radii. For $a = 3/2$, equation (5) predicts $L_\gamma \approx 30L_X$, an observationally interesting number ($\S 3$), while for $a = 1/2$, the predicted gamma-ray luminosity is certainly undetectable, $L_\gamma \approx 10^{-5}L_X$.

### 2.1. Uncertainties in Bondi-like models ($a = 3/2$)

Several models of quasi-spherical accretion (Bondi, ADAF) predict a nearly free-fall radial velocity and, as a consequence, $a = 3/2$. In this case, the primary uncertainty in the $L_\gamma/L_X$ estimate of the previous section is the proton temperature: $\theta_p$ could be smaller than $\sim 0.1$ near the black hole. A priori this is quite worrying because of the strong temperature dependence of the pion reaction rate.

We do not believe that this uncertainty poses a serious threat to the estimate of equation (5). Relativistic corrections to the classical Bondi solution are small (Shapiro 1973). As we explain below, the corrections due to rotation in the ADAF solution are relatively small as well.
In principle, ADAF models can have low proton temperatures near the event horizon (e.g., $\theta_p \lesssim 0.03$). The low-temperature solutions, however, require small values of the dimensionless viscosity $\alpha$, while numerical simulations and theoretical arguments (see §2.2) show that canonical ADAF models are only realizable if $\alpha$ is relatively large, roughly $\alpha \gtrsim 0.1$.

For large $\alpha$ equation (1) is a reasonable approximation of even general relativistic calculations of the structure of ADAFs (Gammie & Popham 1998, Popham & Gammie 1998; hereafter GP).

For non-rotating black holes and $\alpha \gtrsim 0.1$, for example, our temperature profiles match those of GP very well. They find maximal temperatures of $\theta_p \approx 0.1$, consistent with our value. For rapidly spinning black holes, their temperatures are yet higher, reaching $\theta_p \approx 0.3$. In addition, the density profile given by equation (1) is a reasonable approximation of the global calculations for large $\alpha$. Self-similar solutions predict radial velocities $\sim \alpha c_s$, where $c_s$ is the sound speed of the gas. At small radii, however, the accreting gas must pass through a sonic point on its way into the black hole. For large $\alpha$ the “natural” radial velocity of the flow is of order the sound speed, so little deviation from self-similarity is required to match onto the sonic transition.

To test the estimate of equation (5) we calculated the expected gamma-ray to x-ray luminosity ratio using several of GP’s models and found generally good agreement. For a non-rotating black hole and an accretion flow with $\alpha \approx 0.3$, for example, the more detailed calculation yields $L_\gamma \approx 10 L_X$ for $E_X = 10$ keV, in reasonable agreement with equation (5).

It is also important to emphasize that gamma-ray emission from pion decay is unlikely to be as sensitive to temperature as suggested by the simple thermal model we have considered. The collisionless plasmas of interest should efficiently accelerate protons to relativistic energies; in this case the total gamma-ray luminosity varies only linearly with changes in the thermal energy of the protons since there are always a substantial number of protons above the pion production threshold (see Mahadevan et al. 1997).

Equation (5) predicts a detectable gamma-ray flux only if $a \approx 3/2$. The above considerations suggest that equation (5) should be a good approximation in this limit.

### 2.2. Non Bondi-like accretion models ($a < 3/2$)

Modern theories and numerical simulations of quasi-spherical accretion flows suggest that the mean infall velocity can deviate substantially from the free-fall value, resulting in $a < 3/2$. There

---

3This is not true for small $\alpha$ (e.g., Narayan, Kato, & Honma 1997).

4GP consider several adiabatic indices for the flow; we compare only with $\gamma \approx 5/3$, appropriate for a flow dominated by the energy density of the nearly non-relativistic protons.

5Gruzinov & Quataert (1999) describe a proton heating model which yields very little proton acceleration. However, if shocks or reconnection events occur in the accretion flow, a fraction of protons should be accelerated.
are three scenarios: convection-dominated accretion flows (CDAFs), winds, and turbulent heat conduction.

**CDAF:** Two independent groups have performed numerical simulations of quasi-spherical non-radiating accretion flows with small values of the viscosity parameter (Stone, Pringle, & Begelman 1999; Igumenshchev & Abramowicz 1999). They both find $a = 1/2$ rather than $a = 3/2$. Narayan, Igumenshchev, & Abramowicz (2000) and Quataert & Gruzinov (2000) have explained this in terms of a CDAF. In such a flow angular momentum is efficiently transported inwards by strong radial convection. This nearly cancels the outward transport by magnetic fields, leading to a substantially suppressed accretion rate and a much flatter radial density profile.

**Winds:** For large $\alpha > \sim 0.1$, CDAFs do not appear to be found in numerical simulations (Igumenshchev & Abramowicz 1999); this is because the infall time of the gas is shorter than the convective turnover time, so convection is less dynamically important. For large $\alpha$, however, $\alpha$ may differ from $3/2$ for a different physical reason; strong outflows may drive away most of the accreting mass (Blandford & Begelman 1999; Igumenshchev & Abramowicz 1999).

**Turbulent heat conduction:** Conduction preheats the infalling gas, reducing the accretion rate and flattening the density profile (Gruzinov 1999).

### 3. Application to the Galactic Center

Chandra observations of the Galactic Center detect a point source coincident with the non-thermal radio source Sgr A* to within $\approx 0.5'' \approx 10^5 R_S$. Its $0.1-10$ keV luminosity is $L_X \approx 4 \times 10^{33}$ ergs s$^{-1}$ (Baganoff et al. 2000). It is very plausible that this represents the first x-ray detection of the supermassive black hole at the center of our galaxy.

It is natural to interpret Chandra’s detection as thermal bremsstrahlung from large radii in the accretion flow. As shown in §2, such emission would arise from $r \sim 10^4$; the density required to match the observed luminosity is then $\approx 4 \times 10^3$ cm$^{-3}$. The corresponding accretion rate is $\approx 10^{-5} M_\odot$ yr$^{-1}$, if the radial velocity of the gas is of order the sound speed. This is in good agreement with estimates based on the mass-losing stars in the central parsec of the Galactic Center (e.g., Coker & Melia 1997; Quataert, Narayan, & Reid 1999). The bremsstrahlung interpretation predicts the absence of short timescale variability in the observed x-rays (since the emission arises from large radii). It can also be tested by looking for x-ray line emission in deeper Chandra exposures (Narayan & Raymond 1999).

EGRET observations of the Galactic Center region detect a source (2EG 1746-2852) with $L_\gamma \approx 10^{36}$ ergs s$^{-1}$ and a power law spectrum extending from $\approx 100$ MeV to $\approx 10$ GeV (Merck et al. 1996); it appears to be point like within the $\approx 1^\circ$ resolution of the instrument. Mahadevan et al. (1997) interpreted this emission as arising from an ADAF around the black hole at the Galactic Center. In their more comprehensive models of Sgr A*, however, Narayan et al. (1998) were unable...
to produce gamma-ray emission at the required levels and satisfy other observational constraints. Moreover, the observed spectrum of 2EG 1746-2852 looks very similar to that expected from cosmic rays colliding with a dense cloud of molecular hydrogen.

Our calculation in §2 predicts the expected gamma-ray luminosity from the accretion flow given the x-ray luminosity in thermal bremsstrahlung. We believe that the Chandra observations of the Galactic Center provide this thermal bremsstrahlung luminosity. With this normalization, equation (5) predicts \( L_\gamma \approx 10^{35} \text{ ergs s}^{-1} \) for \( a = 3/2 \). This is well above the \( \approx 2 \times 10^{33} \text{ ergs s}^{-1} \) detection threshold of the forthcoming Gamma-ray Large Area Space Telescope (GLAST).

In addition, GLAST’s angular resolution is expected to be significantly better than that of EGRET (for, among other things, the express purpose of identifying unidentified EGRET sources). GLAST will therefore likely have the capability of distinguishing a gamma-ray counterpart of Sgr A* (if it indeed exists) from 2EG 1746-2852.

4. Discussion

We have argued that the ratio of the \( \approx 100 \text{ MeV} \) gamma-ray luminosity to the \( \sim 10 \text{ keV} \) x-ray luminosity of a spherical accretion flow depends primarily on its radial density profile (where \( n \propto r^{-6} \)). In particular, for canonical spherical accretion flow models with \( a = 3/2 \), \( L_\gamma \approx 30L_X \); for \( a < 3/2 \), \( L_\gamma \ll L_X \).

Our analysis predicts the \( \approx 100 \text{ MeV} \) gamma-ray luminosity expected from the accretion flow onto the supermassive black hole at the center of our galaxy (§3): \( L_\gamma \approx 10^{35} \text{ ergs s}^{-1} \) if \( a = 3/2 \) while \( L_\gamma \approx 10^{29} \text{ ergs s}^{-1} \) if \( a = 1/2 \). For \( a = 3/2 \), this estimate is nearly two orders of magnitude above the detection threshold of the GLAST telescope. We expect, however, that no gamma-rays will be observed coincident with the black hole, supporting theoretical suggestions (see §2.2) that the density profile in spherical accretion flows is significantly flatter than the canonical \( r^{-3/2} \) profile.

We thank Charles Gammie and Bob Popham for the use of their global models of ADAFs, Fred Baganoff for information about Chandra observations of the Galactic Center, and John Bahcall for discussions and comments. EQ is supported by NASA through Chandra Fellowship PF9-10008, awarded by the Chandra X–ray Center, which is operated by the Smithsonian Astrophysical Observatory for NASA under contract NAS 8-39073. AG was supported by the W. M. Keck Foundation and NSF PHY-9513835.

\[6\text{ see http://glast.gsfc.nasa.gov/SRD}\]
REFERENCES

Baganoff, F. K., Bautz, M., Brandt, N., Cui, W., Doty, J., Feigelson, E., Garmire, G., Maeda, Y., Morris, M., Pravdo, S., Ricker, G., and Townsley, L. 2000, Ap J Letters, in preparation

Blandford, R.D. & Begelman, M.C., 1999, MNRAS, 303, L1

Bondi, H., 1952, MNRAS, 112, 196

Coker, R. & Melia, F., 1997, Ap J, 488, L149

Colpi, M., Maraschi, L., & Treves, A., 1986, Ap J, 31, 150

Dahlbacka, G.H., Chapline, G.F., & Weaver, T.A., 1974, Nature, 250, 73

Dermer, C., 1986, Ap J, 307, 47

Gammie, C. F. & Popham, R., 1998, Ap J, 498, 313

Gruzinov, A., 1999, in Proceedings IAU Symposium 195, in press (astro-ph/9908027)

Gruzinov, A. & Quataert, E., 1999, Ap J, 520, 849

Igumenshchev, I.V. & Abramowicz, M. A., 1999, MNRAS, 303, 309

Mahadevan, R., Narayan, R., & Krolik, J. 1997, Ap J, 486, 268

Merck, M. et al., 1996, A&AS, 120, 465

Narayan, R., Kato, S., & Honma, F., 1997, Ap J, 476, 49

Narayan, R., Igumenshchev, I. V., & Abramowicz, M. A., 2000, Ap J in press (astro-ph/9912449)

Narayan, R., Mahadevan, R., Grindlay, J.E., Popham, R.G., & Gammie, C., 1998a, Ap J, 492, 554

Narayan, R. & Raymond, R., 1999, Ap J, 515, L69

Narayan, R. & Yi, I., 1994, Ap J, 428, L13

Narayan, R. & Yi, I., 1995, Ap J, 444, 231

Popham, R. & Gammie, C. F., 1998, Ap J, 504, 419

Quataert, E., Narayan, R., & Reid, M. J., 1999, Ap J, 517, L101

Quataert, E. & Gruzinov, A., 2000, Ap J in press (astro-ph/9912440)

Rees, M. J., Begelman, M. C., Blandford, R. D., & Phinney, E. S., 1982, Nature, 295, 17

Rybicki, G. & Lightman, A., 1979, Radiative Processes in Astrophysics (New York: John Wiley & Sons)
Shapiro, S. L., 1973, ApJ, 180, 531

Shvartsman, V. F., 1971, Soviet Astr. - A. J., 15, 377

Stone, J. M., Pringle, J. E., & Begelman, M. C., 1999, MNRAS, 310, 1002