A Thermal Bremsstrahlung Model For the Quiescent X-ray Emission from Sagittarius A*

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ABSTRACT

I consider the thermal bremsstrahlung emission from hot accretion flows (Bondi/ADAFs), taking into account the finite size of the observing telescope's beam ($R_{\text{beam}}$) relative to the Bondi accretion radius ($R_A$). For $R_{\text{beam}} \gg R_A$ soft X-ray emission from the hot interstellar medium surrounding the black hole dominates the observed emission while for $R_{\text{beam}} \ll R_A$ hard X-ray emission from the accretion flow dominates. I apply these models to Chandra observations of the Galactic Center, for which $R_{\text{beam}} \approx R_A$. I argue that bremsstrahlung emission accounts for most of the “quiescent” (non-flaring) flux observed by Chandra from Sgr A*; this emission is spatially extended on scales $\sim R_A \sim 1''$ and has a relatively soft spectrum, as is observed. If accretion onto the central black hole proceeds via a Bondi or ADAF flow, a hard X-ray power law should be present in deeper observations with a flux $\sim 1/3$ of the soft X-ray flux; nondetection of this hard X-ray component would argue against ADAF/Bondi models. I briefly discuss the application of these results to other low-luminosity AGN.

Subject Headings: Galaxy: center — accretion, accretion disks

1. Introduction

Spherical Bondi accretion predicts that the interstellar medium around a black hole should be gravitationally captured on scales of $R_A \approx GM/c_s^2$, where $M$ is the mass of the black hole and $c_s$ is the sound speed of gas in the vicinity of $R_A$ (e.g., Bondi & Hoyle 1944; Shvartsman 1971). The same is true for hot accretion flow models that include dynamically important angular momentum, such as advection-dominated accretion flows (ADAFs; e.g., Ichimaru 1977; Rees et al. 1982; Narayan & Yi 1994) and its variants (e.g., Blandford & Begelman 1999). For radii $\lesssim R_A$ the captured gas accretes onto the central black hole and the dynamics is determined by accretion physics rather than interstellar medium physics.
At a minimum, the gas in Bondi and ADAF models emits thermal bremsstrahlung emission from radii \( \lesssim R_A \) (e.g., Narayan et al. 1998; Di Matteo et al. 1999, 2000). Additional X-ray emission from synchrotron or inverse Compton processes in the accretion flow or jet can also be present depending on the accretion rate and the efficiency of electron acceleration (e.g., Narayan et al. 1998; Markoff et al. 2001; Yuan et al. 2002; Narayan 2002). For sufficiently low-luminosity systems bremsstrahlung emission may dominate over other emission processes in the X-ray band; e.g., Narayan et al. (1999; see Fig. 6) found that bremsstrahlung dominated for \( L_X \lesssim 10^{-8}L_{\text{Edd}} \). This range of luminosities is now routinely probed by Chandra observations (e.g., Ho et al. 2001). In particular, for the Galactic Center \( L_X \sim 10^{-11}L_{\text{Edd}} \) (Baganoff et al. 2002) and so it is a priori plausible that bremsstrahlung contributes significantly to the observed emission.

For a given system, the relative contribution of the accretion flow (\( R \lesssim R_A \)) and the ambient medium (\( R \gtrsim R_A \)) to the thermal bremsstrahlung emission depends on the size of the observing telescope’s beam in units of the Bondi accretion radius. For \( R_{\text{beam}} \gg R_A \) the ambient medium dominates the observed emission while for \( R_{\text{beam}} \ll R_A \) the accretion flow does. The interpretation of observed data therefore depends sensitively on \( R_{\text{beam}}/R_A \).

For ambient temperatures of \( \approx 1 \text{ keV} \), \( R_A \approx 0.07 \text{ pc} \) for the \( 2.6 \times 10^6 M_\odot \) black hole at the Galactic Center and \( \sim 30 \text{ pc} \) for the \( \sim 10^9 M_\odot \) black holes in massive elliptical galaxies such as M87, NGC 4472, and NGC 1399 (for the Galactic Center, see Genzel et al. 1997 and Ghez et al. 1998 for a black hole mass estimate and Baganoff et al. 2002 for a temperature measurement; for elliptical galaxies, see, e.g., Gebhardt et al. 2000 and Ferrarese & Merritt 2000 for black hole mass estimates and Loewenstein et al. 2001 for central temperature measurements). For comparison, the \( \approx 1'' \) angular resolution of the Chandra X-ray Observatory corresponds to a distance of \( \approx 0.04 \text{ pc} \) at the Galactic Center and \( \approx 85 \text{ pc} \) in nearby X-ray clusters such as Virgo and Fornax. Chandra observations thus probe length scales comparable to the Bondi accretion radius for a number of supermassive black holes. In this paper I present models for the bremsstrahlung emission from hot accretion flows that can be applied to Chandra observations with \( R_{\text{beam}} \sim R_A \).

This paper is organized as follows. In the next section (§2) I show X-ray spectra for bremsstrahlung emission from Bondi accretion flows that explicitly account for the finite size of the observing telescope’s beam. I then compare these predictions with Chandra observations of Sgr A* at the Galactic Center (§3). In §4 I conclude and discuss additional applications of these results.
2. Predicted Spectra

Figure 1 shows the density and temperature profiles for spherical accretion onto a central black hole; the radius is in units of the Bondi accretion radius, the temperature is in Kelvin, and the density units are arbitrary. In these models the accretion flow is self-consistently “matched” onto an external ambient medium; this is important when considering observations with $R_{\text{beam}} \sim R_A$ since one cannot always assume that the asymptotic ($R \ll R_A$) accretion flow structure is directly observed. The solid lines in Figure 1 are for the original Bondi problem of accretion from a uniform medium, while the dotted lines are for accretion from a stratified medium in which the ambient density decreases with distance from the central black hole as $\rho \propto R^{-1}$ for $R > \sim R_A$ (these results are based on calculations described in Quataert & Narayan 2000). For both models in Figure 1 the ambient medium is assumed to have a temperature of $\approx 1$ keV. Although it needs to be checked on a case by case basis, the stratified models are probably a better approximation of the real interstellar medium around supermassive black holes. For example, in X-ray clusters the density of gas typically varies as $\sim R^{-1}$ (e.g., Fabian 1994), though Chandra observations indicate that the density profile may flatten in the central parts of some systems (see, e.g., Di Matteo et al. 2002 for M87). For the Galactic Center I show below that the stratified model is appropriate.

Although the detailed calculations presented in Figure 1 are for spherical accretion without angular momentum, similar results are expected for advection-dominated accretion flow models that include angular momentum. This is because ADAFs have density and temperature profiles very similar to the Bondi models in Figure 1 (e.g., Narayan & Yi 1994). Recent analytical and numerical work indicates, however, that ADAF models may not describe the structure of radiatively inefficient accretion flows (e.g., Blandford & Begelman 1999; Quataert & Gruzinov 2000; Hawley & Balbus 2002). In particular the density profiles in the above references are flatter than in Figure 1, i.e., the density increases more slowly with decreasing radius for $R \lesssim R_A$. In §4 I discuss the implications of these results for the bremsstrahlung emission from hot accretion flows.

Figure 2 shows the X-ray bremsstrahlung spectra that result from the density and temperature profiles in Figure 1; the left panel (dotted lines) is for the stratified ambient medium while the right panel (solid lines) is for the uniform ambient medium. The spectra are shown for different values of the size of the observing telescope’s beam in units of the Bondi accretion radius. Each spectrum was calculated using the standard non-relativistic bremsstrahlung formula (e.g., Rybicki & Lightman 1979).

For each spectrum in Figure 2 the density outside $R_{\text{beam}}$ was set to zero so that the emission is dominated by regions along the line of sight which are $\lesssim R_{\text{beam}}$ from the central object. In practice, this requires that the density decrease at least as fast as $R^{-1/2}$ far from
the central object \((R \gtrsim R_{\text{beam}})\) so that these regions do not contribute to the integral of the bremsstrahlung emissivity along the line of sight. This is indeed the case for the stratified models in Figure 2a since \(\rho \propto R^{-1}\) at large radii. The uniform ambient medium models in Figure 2b are, however, somewhat artificial because the spectra depend on the truncation of the density outside \(R_{\text{beam}}\). They are included primarily to illustrate the sensitivity of the predicted spectra to the structure of the ambient medium on scales \(\gtrsim R_A\).

Figure 2 shows how the bremsstrahlung spectra depend on \(R_{\text{beam}}/R_A\). For \(R_{\text{beam}} \gg R_A\) the ambient interstellar medium dominates the observed emission and a soft X-ray spectrum is expected (upper curves); the Bondi flow contributes a weak underlying hard X-ray power law that can only be observed with a very high signal to noise spectrum. For \(R_{\text{beam}} \ll R_A\), on the other hand, the accretion flow dominates the observed emission and the hard X-ray spectrum characteristic of Bondi accretion flows is predicted (lower curves).

A comparison of the results in Figures 2a & 2b indicates that a careful treatment of the radial stratification of the ambient medium is important for quantitatively interpreting observational data: the relative amount of soft X-ray and hard X-ray emission depends on both \(R_{\text{beam}}/R_A\) and the structure of the ambient medium on scales \(\gtrsim R_A\).

3. Comparison with Chandra Observations of the Galactic Center

As of January 2002, Chandra has observed the Galactic Center for a total of \(\approx 75\) ks over 2 epochs and has convincingly detected a source coincident with the supermassive black hole (Baganoff et al. 2001, 2002). For most of the 75 ks, Sgr A* was in a “quiescent” state characterized by a luminosity \(\approx 2 \times 10^{33}\) ergs s\(^{-1}\) and a soft spectrum. For a brief few ks period in the second epoch, Sgr A* flared dramatically, reaching a luminosity of \(\approx 10^{35}\) ergs s\(^{-1}\) with a hard spectrum.

I focus here on the interpretation of the quiescent emission from the Galactic Center, the properties of which can be summarized as follows:

1. The source is extended with a diameter of \(\approx 1''\).
2. The quiescent flux is the same in the first epoch and the second epoch (separated by over a year) and before and after the flare. Aside from the flare, and a possible precursor, the only evidence for short timescale variability is \(< 3\sigma\).
3. Within 1.5” of Sgr A* the luminosity is \(\approx 2 \times 10^{33}\) ergs s\(^{-1}\) and the spectrum is quite soft, consistent with a 2 keV thermal plasma or a power law with a photon index of \(\Gamma = 1.5 - 2.7\) (see Fig. 2a).
4. Within 10” of Sgr A*, there is diffuse thermal bremsstrahlung emission from hot gas surrounding the black hole (likely produced by stellar winds; e.g., Coker & Melia 1997). The luminosity is \( \approx 2 \times 10^{34} \text{ ergs s}^{-1} \) and the spectrum is consistent with a 1.3 keV thermal plasma, somewhat softer than the spectrum within 1.5”.

As I now explain, bremsstrahlung emission provides a good description of the quiescent Chandra observations of Sgr A* summarized in items 1-4. Note that a 1.5” radius around Sgr A* corresponds to \( R_{\text{beam}} \approx R_A \), while a 10” radius corresponds to \( R_{\text{beam}} \approx 10R_A \).

The ratio of the observed X-ray luminosities within 10” and 1.5” of Sgr A* is only a factor of \( \approx 10 \). Since bremsstrahlung emission scales as \( \sim R^3 \rho^2 \), this implies that the typical gas density at 10” is \( \approx 5 \) times smaller than that at 1.5”. Thus the density of hot gas around Sgr A* decreases roughly as \( \sim R^{-1} \) for \( R \gtrsim R_A \) and the results in Figure 2a describe the bremsstrahlung spectra in Bondi/ADAF models of Sgr A*. Because the gas density decreases quite rapidly for \( R \gtrsim R_A \) (faster than \( R^{-1/2} \)), the emission observed by Chandra is dominated by gas within \( R \ll R_{\text{beam}} \), as was assumed in Figure 2 (i.e., there is very little contribution to the bremsstrahlung emissivity from gas at \( R \gtrsim R_{\text{beam}} \) along the line of sight).

In the temperature profiles shown in Figure 1 and used in Figure 2, I fixed the temperature to be \( \approx 1 \) keV at large radii. This boundary condition was chosen so that the models are consistent with Chandra observations of diffuse soft X-ray emission within 10” of Sgr A* (item 4). The density and luminosity units in Figures 1 and 2 are, however, arbitrary. These results can therefore be applied to any system for which the ambient temperature is \( \sim 1 \) keV. For the Galactic Center, a gas density of \( \approx 20 \text{ cm}^{-3} \) at 10” reproduces the observed luminosity of \( \approx 2 \times 10^{34} \text{ ergs s}^{-1} \). The gas density at 1.5” is then \( \approx 100 \text{ cm}^{-3} \). With the temperature at large radii set by the 10” Chandra observations, and with the above normalization of the density at several radii, there are no additional free parameters or boundary conditions in Bondi accretion models.

Figure 2a shows that the bremsstrahlung spectrum within 1.5” of Sgr A* is expected to be quite soft (\( R_{\text{beam}} \approx R_A \)). It is, however, somewhat harder than the spectrum within 10” (\( R_{\text{beam}} \approx 10R_A \)). This is because the ambient gas is mildly compressed and heated just inside the Bondi accretion radius. The soft X-ray spectrum within 1.5” of Sgr A*, and the slight increase in temperature relative to the 10” observations, are both in excellent agreement with the Chandra observations (see items 3 & 4 and Fig. 2a).

Most existing predictions of the bremsstrahlung emission from Bondi/ADAF models

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1 Without a radial density profile obtained by inverting the observed surface brightness profile, this is the best that one can do to estimate \( \rho(R) \) at large radii.
stress the hard X-ray power law seen at high energies in Figure 2 (e.g., Narayan et al. 1998). This hard X-ray emission is produced at radii \( \ll R_A \) where the flow structure approaches its self-similar scalings of \( \rho \propto R^{-3/2} \) and \( T \propto R^{-1} \). For \( R_{\text{beam}} \approx R_A \), this hard X-ray component is a factor of \( \sim 3 \) times less luminous than the soft X-ray emission produced by gas at \( \sim R_A \) (Fig. 2a; middle curve). Because of the limited photon statistics, the hard X-ray component would be difficult to detect in present \textit{Chandra} observations. Instead, the observations are dominated by soft X-ray emission from gas in the vicinity of the Bondi accretion radius.

As Yuan et al. (2002) noted, the bremsstrahlung interpretation advocated here is strongly supported by the observation that the quiescent X-ray source coincident with Sgr A* is resolved with a size of \( \approx 1'' \approx R_A \) (item 1). Models that invoke synchrotron or synchrotron self-Compton (SSC) emission for the majority of the quiescent emission (e.g., Falcke & Markoff 2000; Liu & Melia 2001) predict a source size \( \sim 10 - 100 \) Schwarzschild radii \( \sim 10^{-4} - 10^{-3} \) arcsec, much less than is observed. The bremsstrahlung model also accounts naturally for the relatively constant level of the quiescent flux (item 2) because the characteristic variability timescale at \( \sim R_A \) is \( \sim 100 \) years.

Although bremsstrahlung emission probably dominates the quiescent flux from Sgr A*, it cannot explain the dramatic X-ray flare observed from the Galactic Center (Baganoff et al. 2001). Instead, this emission is likely due to synchrotron or SSC from hot electrons very close to the black hole (e.g., Markoff et al. 2001). This suggests a model in which bremsstrahlung from \( \sim R_A \) provides the “baseline” flux that dominates the quiescent emission, with a time variable synchrotron and/or SSC contribution that is usually sub-dominant but occasionally flares dramatically.

4. Discussion

In this paper, I have presented model X-ray spectra for bremsstrahlung emission from Bondi accretion flows that explicitly include the contribution from hot ambient gas around the black hole (Fig. 2). These spectra are useful for interpreting \textit{Chandra} observations of very low-luminosity AGN since theoretical models suggest that bremsstrahlung may dominate over other emission processes for \( L \ll L_{\text{Edd}} \) (perhaps \( L_X \lesssim 10^{-8}L_{\text{Edd}} \)). Care must be taken in interpreting observations of these systems because the ambient gas around the black hole contributes significantly to the observed emission if \( R_{\text{beam}} \gtrsim R_A \) (see Fig. 2), as is the case for most known systems even given \textit{Chandra}'s excellent angular resolution.

I have applied these results to \textit{Chandra} observations of Sgr A* at the Galactic Center. I propose that, excluding the large X-ray flare, bremsstrahlung emission from gas in the
vicinity of the Bondi accretion radius dominates the quiescent flux observed from Sgr A*.

This model explains why the observed spectrum is quite soft, why the quiescent flux is relatively constant (i.e., independent of time), and why the source is spatially extended (§3). In this interpretation the quiescent emission from Sgr A* does not presently constrain accretion flow models because the emission arises from gas at \( \sim R_A \), i.e., from the “transition region” between the ambient medium and the accretion flow. If, however, accretion onto the black hole proceeds via a Bondi or ADAF flow, a hard X-ray power law should be detectable in deeper Chandra observations. The flux in this power law comes from gas at \( \ll R_A \) and should be \( \sim 1/3 \) of the soft thermal flux from gas at \( \sim R_A \) (Fig. 2a; middle curve).

It is important to stress that Chandra observations of the Galactic Center directly determine the density and temperature of gas at 1.5" \( \approx R_A \) \( (\approx 100 \text{ cm}^{-3} \) and \( \approx 2 \text{ keV}, \) respectively) and at 10" \( \approx 7R_A \) \( (\approx 20 \text{ cm}^{-3} \) and \( \approx 1 \text{ keV}, \) respectively). These boundary conditions strongly constrain Bondi accretion models and it appears difficult to avoid the hard X-ray power law seen in Figure 2 (if Bondi models are correct).

One caveat is that the models presented here assume that all of the inflowing gas is subsonic at large radii \( (\gtrsim 1") \). Since Sgr A* is believed to be fed by stellar winds with velocities \( \sim 300 - 1000 \text{ km s}^{-1} \) (Najarro et al. 1997), I have effectively assumed that most of the stellar winds have shocked outside \( \approx 1" \). For the X-ray emitting gas observed by Chandra this is probably reasonable since the observed temperature of several keV is comparable to that expected from the shocked stellar winds. There could, however, be a component of cold inflowing gas that is not accounted for in the models presented here.

Advection-dominated accretion flow models require an additional boundary condition on top of the density and temperature needed in Bondi models, namely the rotation rate of the gas at \( \approx R_A \). It would be interesting to explore the predicted spectra from ADAF models as a function of this rotation rate (which is rather uncertain). On physical grounds ADAF models should be very similar to the Bondi models shown here as long as the viscous time at \( \sim R_A \) is shorter than the cooling time; this is easily satisfied for the Galactic Center provided the dimensionless viscosity \( \alpha \) is \( \gtrsim 10^{-3} \). My preliminary calculations of ADAF models accreting from an ambient medium support this conclusion.

Although the presence of an underlying hard X-ray power law at roughly the level predicted here appears relatively robust within the context of ADAF and Bondi models, it does depend sensitively on the structure of the accreting gas at \( R \ll R_A \). Moreover, recent theoretical work suggests that that the dynamics of radiatively inefficient accretion flows may be quite different from that predicted by Bondi and ADAF models (e.g., Blandford & Begelman 1999; Stone et al. 1999; Igumenshchev & Abramowicz 2000; Narayan et al. 2000; Quataert & Gruzinov 2000; Igumenshchev & Narayan 2002; Hawley & Balbus 2002). For a
parameterized density profile of the form $\rho \propto R^{-3/2+p}$ ($0 < p < 1$), large values of $p \sim 1/2 - 1$ are favored over the Bondi/ADAF value of $p = 0$.

It is unclear whether these modifications to the structure of the accretion flow occur as far out as $\sim R_A$ or whether they are confined to regions closer to the black hole. For example, most of the physics that leads to significant deviations from ADAF/Bondi models requires dynamically significant angular momentum (see, however, Igumenshchev & Narayan 2002). It is unclear whether this is appropriate near $\sim R_A$, where most of the detectable bremsstrahlung emission originates. Thus, even if the flow structure is very different in the vicinity of the black hole, Bondi models may be applicable near $\sim R_A$.

If the flow structure is significantly modified in the vicinity of $R_A$, one does not expect to see a hard X-ray power law analogous to the Bondi/ADAF results in Figure 2. The reason is that the bremsstrahlung spectrum from a $\rho \propto R^{-3/2+p}$ density profile is $\nu L_\nu \propto \nu^{1/2-2p}$ (Quataert & Narayan 1999). For $p = 0$ (Bondi/ADAF), a hard X-ray power law is present (Fig. 2) while for $p \sim 1/2 - 1$, the spectrum is soft and so there should be very little hard X-ray emission. Deep Chandra observations of the quiescent emission from the Galactic Center can therefore shed important light on the structure of the accretion flow onto the central black hole. Interpreting the data may be complicated if, as is plausible, SSC and/or synchrotron emission contribute to the quiescent flux at some level. The bremsstrahlung contribution can be isolated by focusing on the least variable segments of the observed data. The strength of thermal X-ray lines also provides a constraint on synchrotron or SSC contributions to the quiescent emission (Narayan & Raymond 1999).

The constraints on an underlying hard X-ray power law can be significantly tightened if there are sufficient counts to fully utilize Chandra’s resolution and extract spectra from a $\approx 0.5''$ region around Sgr A*. As Figure 2a shows, most of the soft thermal emission would then be resolved out (since $R_{\text{beam}} \approx 0.3 R_A$). It might even be possible to construct a radial surface brightness profile of the outer parts of the accretion flow to compare with theoretical models (e.g., Quataert & Narayan 2000; Özel & Di Matteo 2001). For example, in ADAF/Bondi models, the spectrum should harden significantly as $R_{\text{beam}}/R_A$ decreases from 1 to 0.3 (Fig. 2).

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2This is a subtle issue because, even if the angular momentum barrier formally lies at a radius $\ll R_A$, angular momentum can still influence the flow structure out to $\sim R_A$. This is because the flow is causally connected from near the horizon out to large radii.
4.1. Additional Applications

The results in this paper are also useful for interpreting Chandra observations of massive black holes in early type galaxies. In such systems the central black hole may accrete the hot ambient interstellar medium of the host galaxy (e.g., Fabian & Rees 1995; Di Matteo et al. 1999). Loewenstein et al. (2001) reported the nondetection of a central hard X-ray point source in NGC 1399, NGC 4472, and NGC 4636. Given black hole mass estimates from the $M_{bh} - \sigma$ relation (Gebhardt et al. 2000; Ferrarese & Merritt 2000), $R_{\text{beam}} \approx 3, 4, \text{ and } 20 \ R_A$ for these systems. The ambient ISM in elliptical galaxies is typically stratified as $\rho \propto R^{-1}$ so the results in Figure 2a can be used to estimate the expected hard X-ray bremsstrahlung emission from a Bondi or ADAF accretion flow. I find that the hard X-ray flux should be $\sim 0.1, 0.1, \text{ and } 0.025$ of the soft X-ray flux in the central 1” for NGC 1399, NGC 4472, and NGC 4636, respectively. Deeper Chandra observations of NGC 1399 and NGC 4472 may be able to detect emission at this level and would provide interesting constraints on accretion models. One complication in interpreting such observations is that the black hole mass is estimated from the $M_{bh} - \sigma$ relation, not direct dynamical studies. This leads to a factor of few uncertainty in $R_A$. In this respect, M87 is a more promising system since the black hole mass is dynamically determined to be $\approx 3 \pm 1 \times 10^9 M_{\odot}$ (e.g., Macchetto et al. 1997); $R_A$ is thus $\approx 1”$ as in the Galactic Center. Unfortunately, however, unresolved emission from the jet appears to dominate Chandra observations of the nucleus of M87 (Wilson & Yang 2002) and so hard X-ray bremsstrahlung emission will be difficult to detect.

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Fig. 1.— Density and temperature profiles for spherical Bondi accretion. The solid lines are for accretion from a uniform ambient medium while the dotted lines are for accretion from a stratified medium in which the ambient density decreases with radius as $\rho \propto R^{-1}$. The vertical dashed lines help indicate the part of the accretion flow probed by a telescope with $R_{\text{beam}}/R_A = 0.1, 1, \text{ and } 10$ (from left to right). Chandra has $R_{\text{beam}} \approx R_A$ for the Galactic Center and $R_{\text{beam}} \approx 1 - 10R_A$ for a number of elliptical galaxies in nearby X-ray clusters.
Fig. 2.— Bremsstrahlung X-ray spectra using the density and temperature profiles in Figure 1. The spectra are shown for various values of the size of the telescope beam relative to the Bondi accretion radius. Fig. 2a is for accretion from a radially stratified ambient medium (dotted lines in Fig. 1) while Fig. 2b is for accretion from a uniform ambient medium (solid lines in Fig. 1). The best fit spectral slope ($2 - 10$ keV) for quiescent emission from within $1.5''$ of Sgr A* is shown by the solid line in Fig. 2a (1.5” corresponds to $R_{beam} \approx R_{A}$); the dashed lines give the 90% confidence limits (Baganoff et al. 2001).