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Inflow-Outflow Solution with Stellar Winds and Conduction near Sgr A*

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Abstract. We propose a 2-temperature radial dynamical model of plasma flow near Sgr A* and fit the bremsstrahlung emission to extensive quiescent X-Ray Chandra data. The model extends from several arcseconds to black hole (BH) gravitational radius, describing the outer accretion flow together with the infalling region. The model incorporates electron heat conduction, relativistic heat capacity of particles and feeding by stellar winds. Stellar winds from each star are considered separately as sources of mass, momentum and energy. Self-consistent search for the stagnation and sonic points is performed. Most of gas is found to outflow from the region. The accretion rate is limited to below 1% of Bondi rate due to the effect of thermal conduction enhanced by entropy production in a turbulent flow. The X-Ray brightness profile proves too steep near the BH, thus a synchrotron self-Compton point source is inferred with luminosity $L \sim 3 \cdot 10^{32}$ erg/s. We fit the sub-mm emission from the inner flow, thus aiming at a single model of Sgr A* accretion suitable at any radius.

1. Introduction

Our Galaxy is known to host a supermassive black hole (BH) with mass $M \approx 4.5 \cdot 10^6 M_\odot$ at a distance $R \approx 8.4$ kpc (Ghez et al. 2008). The BH exhibits very low luminosity state probably due to inefficient feeding and cooling. The BH is fed by stellar winds within several arcseconds from the compact object roughly around the radius of BH gravitational influence (Cuadra et al. 2008). The stellar winds are expelled at large speeds. They collide, heat up to $\sim 10^7$ K and emit bremsstrahlung X-Rays, observed by Chandra (Baganoff et al. 2003). A small fraction of mass accretes onto the black hole is thus producing the emission in sub-mm and other wavebands. However, the inferred accretion rate within several Schwarzschild radii is 2 orders of magnitude lower (Marrone 2007) than the inferred Bondi accretion rate (Bondi 1952) at several arcseconds. This disparity is resolved in a present work with a point source revealed coincident with Sgr A*. A brief account of observations is made in § 2.. The dynamical model is outlined in § 3.. The results are discussed in § 4..

2. Observations

We analyze ~ 1 Ms of Chandra exposure of Sgr A* and central arcseconds (Muno et al. 2008) significantly improving over the previously analyzed 41 ks exposure

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(Baganoff et al. 2003). As we are interested in the quiescent emission, we bin the observations in 628 s bins and exclude the flaring states with counts triple the mean. We also subtract the point sources and extended bright emission zones, thus extracting the quiescent count surface brightness profile within 5″. Having the extensive data we are able to perform the subpixel spatial binning in rings 0.125″ thickness owing to dithering of spacecraft. The counts from four 90° ring segments centered at Sgr A* are compared in order to test the viability of the radial model. It appears that within 2″ the counts do not differ significantly between ring segments, but the variation was found at $> 2''$. The point spread function (PSF) is extracted by observing the nearby binary J174540.9-290014.

3. Stellar Winds and Dynamical Model

Feeding of the black hole should be a starting point of any accretion model. This approach helps to eliminate a number of arbitrary boundary conditions. A set of ~ 30 wind emitters is believed to supply almost all the matter into the feeding region of Sgr A*. Following Cuadra et al. (2008), we identify the important wind emitters, find the wind speeds and ejection rates. We obtain the orbital data from Paumard et al. (2006); Martins et al. (2007); Lu et al. (2009), assuming the stars either belong to the disk or taken to have the minimum eccentricities. As we are constructing the radial model, the radial feeding function $q(r)$ is produced by smoothing wind inputs over radius between the apocenter and the pericenter for each star (see Fig. 1). The averaged wind velocity is found as a root-mean-square average over stars weighed with the ejection rate. We do not account for orbital velocities of stars in energy input as feeding is dominated by only a few stars close to the BH. S2 star is included into the calculation as it may eject more matter (Martins et al. 2008), than falls onto the BH.

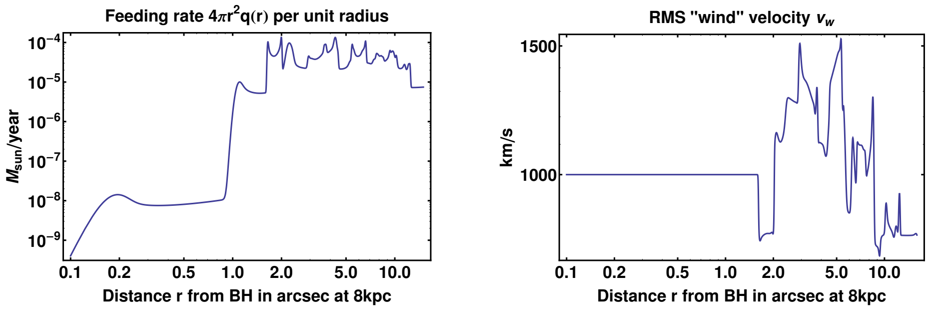

Figure 1. Mass input into the central region around the BH on the left panel. Root-mean-square wind velocity v_w on the right panel.

The dynamical model has sources of mass, radial momentum and energy due to winds (Lamers & Cassinelli 1999). The main feature of the model is the electron thermal conduction proportional to the temperature gradient with conductivity $\kappa = 0.1\sqrt{k_B T_e/m_e} n_e r$ (Johnson & Quataert 2007). Here we have included the factor of 5 inhibition of conductivity in turbulent magnetic field (Narayan & Medvedev 2001). So computed heat flux appears to be below the saturated flux (Cowie & McKee 1976). In reality the inner accretion flow is collisionless and the outer accretion is weakly collisional, however, the single prescription for conductivity gives the reasonable approximation. The realistic behavior of electrons in the inner flow is achieved by using their relativistic heat capacity in the equations of motion, which naturally leads to the ratios T_p/T_e up to 10 even in adiabatic flows. For completeness of the theory we add the direct energy transfer into electrons and protons equivalent to the entropy production, which happens due to viscosity in the rotating flow or due to dissipation of turbulence (Shcherbakov 2008). We assume that the fractions f_e and f_i of available gravitational energy goes to electrons and protons. The Coulomb collisions are included for numerical stability to balance the electron and proton temperature in the outer flow, though they do not have the significant dynamical effect. The effect of gas composition is accounted for by introducing the effective mass $m_{av} \approx 1.245 m_H$ per electron and correspondent reduction in ion gas pressure. These numbers are taken for the solar abundance of elements, which seems to be reasonable for stellar winds (Najarro et al. 2004). Paczhynski-Wiita gravitational potential is employed.

The proposed system of equations has no artificial boundary conditions, but it appears to have an unmatched complexity. We self-consistently solve for the positions of the stagnation point, where gas velocity is zero, and the inner isothermal sonic point (Quataert 2004). The heat flux is set to zero at the point, where $dT_e/dr = 0$ in the Bondi solution near the BH. The outer boundary is either taken to be the isothermal sonic point in the outflow or the point with slightly higher density (for numerical stability). The relaxation technique is used for the 2-temperature system between the inner boundary and the stagnation point, whereas only shooting works outside the stagnation point.

4. Results

Having produced a bunch of dynamical models, we convert the temperature and density radial profiles into the surface brightness profile. We take the up-to-date bremsstrahlung emissivities (see (Gould 1980) and errata) and account for emission by heavy elements, excluding iron. We calculate the spectrum along each

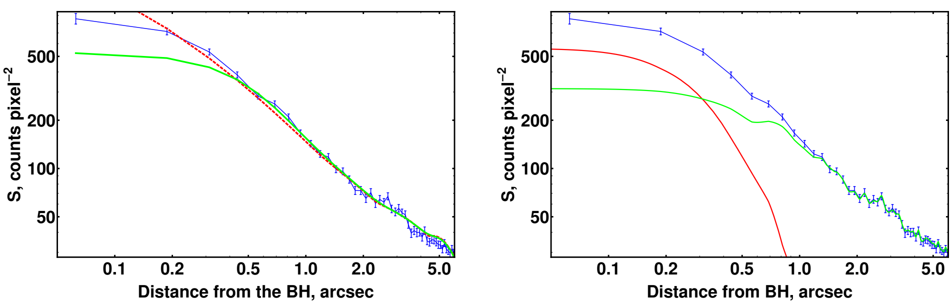

Figure 2. Plots of surface brightness S in observed counts per pixel squared (1 pixel=0.5″). Blue curve with error bars shows the observations. Extended emission model is on the left panel: the green curve shows brightness smoothed by PSF. The model of a point source with $L = 3 \cdot 10^{32}$ erg/s (red) and the residual (green) are on the right panel.

ray and convert it to counts by applying the solar metallicity interstellar absorption (Morrison & McCammon 1983) with hydrogen column $N_H = 10^{23}\text{cm}^{-2}$ and convolving with the response of Chandra. Then we apply the PSF blurring and compare with the observed surface brightness profile. The outer surface brightness profile can be reasonably fitted by a model with $f_e = 0.15$, $f_i = 0.05$, which also leads to the ratio $T_p/T_e \approx 15$ near the BH. However, we find that the inner part of surface brightness curve is too steep for any extended emission. There should be a point source in the center accounting for $^1/_3$ to $^2/_3$ of central surface brightness and having the unabsorbed luminosity about $L = 3 \cdot 10^{32}$ erg/s of monoenergetic 4 keV photons. About the same luminosity is expected from the synchrotron self-Compton (SSC) process near the BH. The search for the best model with the point source continues. We want the best model to reproduce the observed Faraday rotation measure $RM \approx 50\text{cm}^{-2}$(Marrone 2007) and optically thick flux $F_R = 1.73$ Jy at 86 GHz (Krichbaum et al. 2006). An order of magnitude consistency is achieved on the way. The accretion rate appears to be self-consistently limited to $< 1\%$ of Bondi value, thus the connection between the inner accretion flow and the outer accretion flow is established. The future versions will include the angular momentum and use X-Ray spectral information.

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