Decaying Sterile Neutrinos as a Heating Source in the Milky Way Center

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ABSTRACT
Recent Chandra and Newton observations indicate that there are two-temperature components ($T \sim 8$ keV, 0.8 keV) of the diffuse x-rays emitted from deep inside the center of Milky Way. We show that this can be explained by the existence of sterile neutrinos, which decay to emit photons that can be bound-free absorbed by the isothermal hot gas particles in the center of Milky Way. This model can account for the two-temperature components naturally as well as the energy needed to maintain the $\sim 8$ keV temperature in the hot gas. The predicted sterile neutrino mass is between 16-18 keV.

Key words: Dark matter, Milky Way, Interstellar medium

1 INTRODUCTION

Recently, a large amount of diffuse x-ray data have been obtained by Chandra, BeppoSAX, Suzaku and XMM-Newton, giving a complex picture near the Milky Way center (Muno et al. 2004; Rockefeller et al. 2004; Senda et al. 2002; Hamaguchi et al. 2007; Sidoli et al. 1999; Sakano et al. 2004). The data indicates that there exists a high temperature ($\sim$ keV) hot gas near the Milky Way center. Kaneda et al. (1997) suggested that the existence of two-temperature components of the hot gas can explain the observed x-ray spectrum. Sakano et al. (2004) analysed the XMM-Newton data to get 1 keV and 4 keV hot gas components in Sgr A East, a supernova remnant located close to the Milky Way center. Muno et al. (2004) used the data from Chandra to model the temperature of the two components within 20 pc as 0.8 keV and 8 keV. The temperature of the soft component ($T_1 \sim 0.8$ keV) can be explained by 1 percent of kinetic energy by one supernova explosion in every 3000 years near the Milky Way center. The major heating mechanism is the bound-free collisions between the decay photons and the ions in the hot gas. In this optically thick region, the hot gas particles are in photoionization equilibrium. The high metallicity of the gas, $\tilde{Z}_{\text{metal}} > 2$ solar metallicity, enhances the heating rate of the gas and provides enough energy to sustain the high temperature of the hot gas. The energy absorbed in the central region is transferred to the outside optically thin region ($1 - 20$ pc) by collisions among the electrons to share their energy (collisional equilibrium). Also, we assume that the soft and hard components are in equilibrium with different uniform temperatures and they are bounded hydrostatically.

Although the recent MiniBooNE data challenges the LSND result that suggests the existence of eV scale sterile neutrinos (Aguilar-Arevalo et al. 2007), more massive sterile neutrinos (eg. keV) may still exist. The fact that active neutrinos have rest mass implies that righthanded neutrinos should exist which may indeed be massive sterile neutrinos. The existence of the sterile neutrinos has been invoked to explain many phenomena such as reionization (Hansen and Haiman 2004), missing mass (Dodelson and Widrow 1994) and the high temperature of...
the hot gas in clusters (Chan and Chu 2007). Therefore, it is worthwhile to discuss the consequences of the existence of massive sterile neutrinos, which may decay into light neutrinos and photons.

The existence of the small size keV sterile neutrino halo is first suggested by Viollier et al. (1993). The size of a self-gravitating degenerate sterile neutrino halo depends on $m_s$ and total mass $M_s$: $R_s = 0.0006 (M_s/10^8M_\odot)^{-1/3} (m_s/16\text{ keV})^{-8/3}\text{ pc}$. Including the contribution of the baryons, the size will be even smaller. The size of the sterile neutrino halo is upper bounded by $R_s \leq 0.0005\text{ pc}$ (Schoel et al. 2002). This size is very small compared to that of a galaxy and therefore the sterile neutrino halo will hide deeply inside the galactic center (Munyaneza and Viollier 2004). Sterile neutrinos may decay into active neutrinos and become a strong energy source to galaxies and clusters. The decays of keV order sterile neutrinos may also help to solve the cooling flow problem in clusters (Chan and Chu 2007).

2 BOUND-FREE ABSORPTION MODEL

The sterile neutrinos at the center will decay into active neutrinos with decay rate $\Gamma$ by the following process:

$$\nu_s \rightarrow \nu_a + \gamma .$$

(1)

We assume that the energy of decay photons $E_s \approx m_s/2$ is greater than 8 keV because the energy of each photon must be greater than the energy of each electron in the hot gas in order for the latter to gain energy from the photons (Chan and Chu 2007). The decayed photons come from the volume emission of the entire sterile neutrino halo. The distribution of photon energy has a characteristic width determined by the Fermi momentum of the sterile neutrinos $p_F$, which is very small compared with the rest mass of the sterile neutrinos, $p_F/m_s c \sim 10^{-3}$. Therefore, we can approximate the photon spectrum as monochromatic with energy $E_s$.

Since we have not detected any strong lines of such high energy photons from the Milky Way center, the optical depth for decayed photons must be much greater than 1. Therefore, the total energy emitted by the decayed photons must equal to the total energy gained by the electrons ($\sim 10^{40}\text{ erg s}^{-1}$):

$$\sum_i N_i \Gamma (E_s - E_i) P_i \geq 10^{40}\text{ erg s}^{-1},$$

(2)

where $N_i$ is the total number of sterile neutrinos, $E_i$ and $P_i$ are the ionization potential and probability of photon absorption by $i^{th}$ type ion in the hot gas:

$$P_i = \frac{a_i \sigma_{bf,i}}{\sum_i a_i \sigma_{bf,i}} ,$$

(3)

where $a_i$ is the ratio of the number of $i^{th}$ type ions to the total number of ions at 0.8 keV temperature (the number density of the soft component is about ten times more than that of the hard component if they are in equilibrium). The absorption cross section of the $i^{th}$ type ions is largest for H-like and He-like ions, which is given by (Daltabuit and Cox 1972):

$$\sigma_{bf,i} = 10^{-18} \alpha_i \left[ \frac{E_{th,i}}{E_s} \right]^{s_i} \left[ 1 - \alpha_i \right] \left( \frac{E_{th,i}}{E_s} \right)^{s_i+1} \text{ cm}^2. \quad (4)$$

where $\alpha_i$, $E_{th,i}$ and $s_i$ are fitted parameters of a particular $i^{th}$ type ion. The total effective cross section is

$$\sum_i a_i \sigma_{bf,i}. \quad (5)$$

where the number density of hot gas near the center has an isothermal profile:

$$n(r) = n_0 \left( \frac{r}{1\text{ pc}} \right)^{-2} .$$

The average number density within 20 pc of the center is about 1 cm$^{-3}$ which corresponds to $n_0 = 133\text{ cm}^{-3}$. In table 2, we can see that $\tau < \tau_{\text{lower}}$ for $E_s \geq 10\text{ keV}$. Therefore, only $E_s = 8 - 9\text{ keV}$ can be possible for decaying sterile neutrinos as the heating source (see Fig. (1)).

Given this power input ($10^{40}\text{ erg s}^{-1}$), we can estimate the equilibrium temperature of the gas at the center of Milky Way. The ionizing photons are continuously supplied and the heating rate is quite constant as the decay of sterile neutrinos is a slow process (half-life of order Hubble time). The energy absorbed will then be transferred to the other gas particles mainly by conduction. The power loss by Bremsstrahlung radiation of a hot gas with temperature $T$ is $W = 1.4 \times 10^{34}n_e T^{1/2} \text{ erg s}^{-1}$, and the power by its adiabatic expansion is

$$W = PV^{2/3}c_s = PV^{2/3} \left( \frac{kT}{m_s} \right)^{1/2} ,$$

(8)

where $P$, $V$, $c_s$, $\gamma$ and $m_s$ are pressure, volume, sound speed, adiabatic index of the hot gas and mean mass of the gas particles respectively. The energy loss due to Bremsstrahlung is negligible, being only 0.3 percent of the adiabatic cooling (Muno et al. 2004). We can therefore solve for the equilibrium temperature of the gas using Eq. (8). The temperature maintained in this process is given by
Table 1. Metal abundances we have used in the model.

| Element | Atomic number $Z$ | Metallicity $\tilde{Z}_{\text{metal}}$ | $a_i(10^{-4})$(H-like) | $a_i(10^{-4})$(He-like) |
|---------|------------------|----------------------------------|-------------------|-------------------|
| C       | 6                | 3                               | 6.9               | 2.7               |
| N       | 7                | 3                               | 1.7               | 0.84              |
| O       | 8                | 3                               | 16                | 9.6               |
| Ne      | 10               | 3                               | 2.5               | 1.9               |
| Mg      | 12               | 3                               | 1.0               | 0.89              |
| Si      | 14               | 8.9                             | 3.0               | 2.8               |
| S       | 16               | 2.7                             | 0.43              | 0.42              |
| Ar      | 18               | 1.8                             | 0.066             | 0.066             |
| Ca      | 20               | 2.5                             | 0.056             | 0.056             |
| Fe      | 26               | 3.8                             | 1.8               | 1.8               |

Figure 1. The allowed $N_\sigma$ and $m_\sigma$ by using the constraints in Eq. (2) (dashed line), Eq. (5) (solid line) and by the temperature of the hard component ($E_s \geq 8$ keV)(dotted line).

$$ T \approx V^{-4/9} \left( \frac{\dot{W}}{n_i k} \right)^{2/3} \left( \frac{m_g}{\gamma k} \right)^{1/3} $$

If $\dot{W} = 10^{40}$ erg s$^{-1}$ within 20 pc, then $T \approx 8$ keV. In fact, the situation is similar to energy absorption in x-ray emitting nebulae. However, in a normal x-ray nebula, the x-ray source is usually far away from the gas cloud, whereas in our model the source is located at the center of the gas cloud. Furthermore, the energy absorption in a normal x-ray nebula is about $10^{30}$ erg s$^{-1}$ so that the temperature of the nebula is about eV order (Leahy et al. 1994). In our model, the energy absorption is $10^{40}$ erg s$^{-1}$, which can maintain the temperature of the hard component at 8 keV.

3 TWO-TEMPERATURE COMPONENTS

When the gas particles are in thermal equilibrium,

$$ \tilde{\Gamma}(n_g, T) = \tilde{\Lambda}(n_g, T), $$

where $n_g$ is the number density of the gas particles, $\tilde{\Gamma}$ and $\tilde{\Lambda}$ are the heating and cooling rates respectively. It is possible to have multi-temperature components in the hot gas, because there may be more than one solutions ($n_g, T$) satisfying Eq. (10). The criterion for stability of the solution is (Bowers and Deeming [1984]):

$$ \frac{\partial}{\partial T}(\tilde{\Gamma} - \tilde{\Lambda}) + \frac{\partial}{\partial \rho}(\tilde{\Gamma} - \tilde{\Lambda}) \left( \frac{\partial \rho}{\partial T} \right) < 0, \quad (11) $$

where $\rho$ and $P$ are the mass density and pressure of the hot gas. Since the relaxation time of electron-electron collisions is less than that of ion-electron collisions, the temperature of electrons $T_e$ may be different from the temperature of ions $T_i$ in general. The total heating rate inside the gas cloud ($r \lesssim R \approx 20$ pc) is given by:

$$ \tilde{\Gamma} \sim \tilde{\Gamma}_0 n_g \sum_i a_i \sigma_{bf,i}, $$

where $\tilde{\Gamma}_0$ is a constant that depends on the size of the region. The cooling rate of x-ray emitting hot gas by Bremsstrahlung radiation is:

$$ \tilde{\Lambda} \sim \tilde{\Lambda}_0 n_e n_g \sum_i a_i Z_i^2 e^{-2I_i/kT_e} T_e^{1/2}, $$

where $\tilde{\Lambda}_0$ is a constant, $I_i$ and $Z_i$ are the ionization energy and charge of the $i^{th}$ type ions respectively. Since the entire gas cloud is optically thin for $r \sim$ pc and heavy metal ions are concentrated at the central region (Sakano et al. 2004), the bound-free absorption of the broad-band Bremsstrahlung photons is suppressed ($\tau \lesssim 1$) in a large fraction of the volume of the cloud, so that most of the Bremsstrahlung photons can escape the gas cloud eas-
ily. When the hot gas particles are in thermal equilibrium, $\Gamma = \dot{\Lambda}$, and the pressure is given by:

$$P = P_0 \frac{T_{\text{keV}}^{3/2}}{2 \pi} \sum_i a_i Z_i^2 e^{-a_i T_i},$$

(14)

where $P_0 = (1 \text{ keV})^{3/2} k T_0/\dot{\Lambda}_0$ and $T_{\text{keV}} = T_e/(1 \text{ keV})$.

Fig. (2) shows the relation between $P$ and $T_e$ by using the mean metallicity within 20 pc (Muno et al. 2004). We notice that for some values of $P$ there are two different values of $T_e$. By putting the heating and cooling rates into Eq. (11), we get the criterion for stable solutions:

$$\sum_i a_i \frac{\sigma_{\text{ff},i}}{Z_i^2} e^{-a_i T_i} \left[ \sum_i a_i Z_i^2 e^{-a_i T_i} \right] \leq \sum_i \sigma_{\text{ff},i} \left[ a_i - T_e \frac{d a_i}{dT_e} \right],$$

where $\beta_i = 2 I_i/k T_i$. We impose a free parameter $\mu$ such that $T_e = \mu T_i$. We define $A$ and $B$ to be the expressions on the left and right hand sides of the inequality in Eq. (15) respectively. In Fig. (3), we plot $A - B$ against $T_e$ for two values of $\mu$. When $\mu = 3.2$ and $\mu = 6.9$, 0.8 keV $< T_e < 4$ keV and 1.8 keV $< T_e < 8$ keV are unstable solutions respectively as $A - B > 0$. We also indicate the unstable regions in Fig. (3), and we notice that a two-temperature phase may exist with $T_e \geq 8$ keV and $T_e \leq 0.8$ keV for $3.2 \leq \mu \leq 6.9$. In Fig. (2), we can see that if there are less large-Z metal ions (especially iron) in the hot gas, more hot gas particles will shift to the lower temperature phase and only one equilibrium solution may be obtained. Clearly, our model can account for the two-temperature structure of the hot gas near the Milky Way center.

### 4 DISCUSSION

To explain the origin of the hard component, Muno et al. (2004) make use of magnetic reconnection driven by the turbulence that supernovae generate in the interstellar medium. Magnetic reconnection can heat the hot gas to $k T \sim B_{\text{center}}^2/8 \pi n_g$. For $n_g \sim 0.1 \text{ cm}^{-3}$, $B_{\text{center}} \sim 0.2 \text{ mG}$, $k T \sim 8$ keV. However there is not enough evidence to support whether this mechanism can maintain the high temperature of the hard component (Muno et al. 2004).

In our model, we have assumed that there exists a sterile neutrino halo with $m_s = 16 - 18$ keV in the Milky Way center, which decay to emit $\gamma$ with life-time of cosmological order. It provides a large amount of energy to the hot gas and maintains the extremely high temperature. The bound-free collisions provide enough energy to the two different temperature components and maintain their temperatures. At the same time, a stable two-temperature structure in the hot gas can be explained by this heating mechanism naturally. The uniform emission of the soft and hard components suggests that they may come from similar physical processes (Muno et al. 2004). In our model, both components indeed share the same source of energy - the 8-9 keV photons emitted by the decays of sterile neutrinos. In our model, the sterile neutrinos may not be the major component of dark matter. Therefore, any bounds on $m_s$, assuming they are the major dark matter candidate does not constrain our model severely. The heating rate in the Milky Way center is time dependent as there is a decreasing number of sterile neutrinos. Therefore, if two galaxies have similar chemical compositions, the heating rate is greater for the large redshift one, which has more particles in the higher temperature component. We therefore predict that the hard component of the x-rays would be stronger for large redshift and metal-rich galaxies. Moreover, if a galaxy has lower metallicity, then only a single temperature component may be observed instead of two (see Fig. (2)).

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Figure 2. Pressure ($P$) versus temperature ($T$) of the hot gas, given by Eq. (14) for $\tilde{Z}_{Fe} = 0.71$ (solid lines) and $\tilde{Z}_{Fe} = 0.14$ (dashed lines) for two different values of $\mu$.

Figure 3. The difference between the left hand side ($A$) and right hand side ($B$) of Eq. (15) versus $T_e$ for $\mu = 2.7$ (dashed line), $\mu = 3.2$ (solid line) and $\mu = 6.9$ (dotted line).

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