Decaying sterile neutrinos as a heating source in the Milky Way centre

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ABSTRACT
Recent Chandra and XMM–Newton observations indicate that there are two-temperature components \((T \sim 8 \text{ keV}, 0.8 \text{ keV})\) of the diffuse X-rays emitted from deep inside the centre 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 centre of Milky Way. The model can account for a stable configuration of the two-temperature components hot gas naturally as well as the energy needed to maintain the \(\sim 8 \text{ keV}\) temperature in the hot gas. The predicted sterile neutrino mass is between 16–18 keV.

Key words: dark matter.

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 centre (Sidoli et al. 1999; Senda, Murakami & Koyama 2002; Muno et al. 2004; Rockefeller et al. 2004; Sakano et al. 2004; Hamaguchi et al. 2007). The data indicate that there exists a high temperature \((\sim \text{keV})\) hot gas near the Milky Way centre. 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 and 4 keV hot-gas components in Sgr A East, a supernova remnant located close to the Milky Way centre. Later Muno et al. (2004) used the data from Chandra to model the temperature of the two components within 20 pc as 0.8 and 8 keV. The temperature of the soft component \((T_1 \sim 0.8 \text{ keV})\) can be explained by 1 per cent of kinetic energy by one supernova explosion in every 3000 yr near the Milky Way centre, corresponding to power \(\sim 3 \times 10^{48} \text{ erg s}^{-1}\) (Muno et al. 2004). However, the high temperature of the hard component \((T_2 \sim 8 \text{ keV})\) cannot be explained satisfactorily. The power needed to sustain the high temperature is about \(10^{48} \text{ erg s}^{-1}\). Moreover, the emission of the hard component is distributed much more uniformly than the soft component and the intensity of the two components are correlated, which suggest that they are produced by related physical processes (Muno et al. 2004).

In this article, we present a model to explain the two-temperature composition, as well as the high temperature and uniform emission of the hard component obtained by Chandra within 20 pc. We assume that there are sterile neutrinos with rest mass \(m_\nu \geq 16 \text{ keV}\) in the deep Galactic Centre and their decay photons continuously supply the energy of the hard X-ray emission. The sterile neutrino halo is located at the centre of a 20-pc radius gas cloud which is heated by the decayed photons. Most photons are absorbed near the centre \((\sim 0–1 \text{ pc})\) of Milky Way and the energy is subsequently transferred to the surrounding gas. 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, \(Z_{\text{metal}} \geq 2–3\) solar metallicity, enhances the heating rate of the gas and provides enough energy to sustain the high temperature of the hard component. The absorbed energy in the central region is transferred to the outside optically thin region \((1–20 \text{ pc})\) 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 challenge the Liquid Scintillator Neutrino Detector (LSND) result that suggests the existence of eV scale sterile neutrinos (Aguilar-Arevalo et al. 2007), more massive sterile neutrinos (e.g. keV) may still exist. The fact that active neutrinos have rest mass implies that right-handed 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 & Haiman 2004), missing mass (Dodelson & Widrow 1994) and the high temperature of the hot gas in clusters (Chan & 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, Trautmann & Tupper (1993). The size of a self-gravitating degenerate sterile neutrino halo depends on \(m_\nu\) and total mass \(M_c : R_c = 0.0006 (M_c / 10^8 M_\odot)^{1/3} (m_\nu / 16 \text{ keV})^{-8/3} \text{ pc}\). Including the contribution of the baryons, the size will be even smaller. The size of the sterile neutrino halo is upper bounded by \(R_c \leq 0.0005 \text{ pc}\) (Schödel 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 Centre (Munyaneza & Viollier 2002). 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 & Chu 2007).

2 BOUND-FREE ABSORPTION MODEL

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

$$v_\nu \rightarrow v_\alpha + \gamma.$$  \hspace{1cm} (1)

We assume that the energy of decay photons $E_\gamma \approx m_\nu/2$ 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 & 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, $p_F/m_\nu \sim 10^{-3}$. Therefore, we can approximate the photon spectrum as monochromatic with energy $E_\gamma$.

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

$$\sum N_i \Gamma(E_\nu - E_i) P_i \geq 10^{40} \text{erg s}^{-1},$$  \hspace{1cm} (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 ions in the hot gas.

$$P_i = \frac{\alpha_i \sigma_{bf,i}}{\sum_j \alpha_j \sigma_{bf,j}},$$  \hspace{1cm} (3)

where $\alpha_i$ 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 10 times more than that of the hard component if they are in equilibrium). The absorption cross-section of the $i$th type ions is about 10 times more than that of the hard component (half-life of order Hubble time). The absorbed energy will then be transferred to the other gas particles mainly by conduction. The absorbed energy will then be transferred to the other gas particles mainly by conduction. The absorbed energy will then be transferred to the other gas particles mainly by conduction.

A higher energy of the decayed photons will result in a smaller cross-section and optical depth. The mass density profile of Milky Way centre can be modelled by a power law $\rho \sim r^{-1.8}$ (Schödel et al. 2002). For simplicity, we assume that the number density of hot gas near the centre has an isothermal profile:

$$n(r) = n_0 \left( \frac{r}{1 \text{ pc}} \right)^{-2}.$$  \hspace{1cm} (7)

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

Given this power input ($10^{40}$ erg s$^{-1}$), we can estimate the equilibrium temperature of the gas at the centre 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 absorbed energy 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

$$\Lambda \approx 1.4 \times 10^{-27} n_T^{3/2} T^{1/2} \text{ erg s}^{-1} \text{ cm}^{-3},$$

and the power by its adiabatic expansion is:

$$W = PV^{2/3} c_s = PV^{2/3} \left( \frac{\gamma k T}{m_\gamma} \right)^{1/2},$$

where $P$, $V$, $c_s$, $\gamma$ and $m_\gamma$ 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, which is being only 0.3 per cent of the adiabatic cooling

Table 1. Metal abundances we have used in the model.

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

$\tilde{Z}_{\text{metal}}$ is the metallicity of the gas near the Milky Way centre (2.6 $\times$ 10$^9$ M$_\odot$) (Schödel et al. 2002).

To constrain the value of $E_\gamma$, we can consider the upper limit of X-ray luminosity in the 2–10 keV band near the Milky Way centre, which is $3 \times 10^{36}$ erg s$^{-1}$ (Muno et al. 2004). We can obtain the lower limit of the optical depth $\tau_{\text{lower}}$ by

$$n_i \Gamma E_\gamma \leq 3 \times 10^{36} \text{ erg s}^{-1},$$  \hspace{1cm} (5)

where $\tau$ is the optical depth for decayed photons which is given by

$$\tau = \int n(r) \sum_i \sigma_{bf,i} dr.$$  \hspace{1cm} (6)

The metallicity $\tilde{Z}_{\text{metal}}$ near the Milky Way centre can reach 2–3 $\tilde{Z}_{\text{metal}}$ ( solar metallicity) (Sakano et al. 2004). The metal ions with the largest cross-section include Si ($\tilde{Z}_i = 8.9 \tilde{Z}_{\text{Si,}}$), S ($\tilde{Z}_i = 2.7 \tilde{Z}_{\text{S,}}$), Ar ($\tilde{Z}_i = 1.8 \tilde{Z}_{\text{Ar,}}$), Ca ($\tilde{Z}_i = 2.5 \tilde{Z}_{\text{Ca,}}$) and Fe ($\tilde{Z}_i = 3.8 \tilde{Z}_{\text{Fe,}}$) (see Table 1) (Sakano et al. 2004). Assuming $\tilde{Z}_{\text{metal}} = 3 \tilde{Z}_{\text{metal,}}$ ( solar metallicity) for other metals and $\Gamma = (3-6) \times 10^{-16}$ s$^{-1}$ (the best-fitting value that can solve the cooling flow problem) (Chan & Chu 2007), we can obtain $N_i$ and the total mass of the sterile neutrino halo ($M_\nu = N_i m_\nu$) by equation (2) for different $E_\gamma$ (see Table 2). The value of $M_\nu$ obtained ($\sim 10^9 M_\odot$) is far below the upper bound of the total mass near the Milky Way centre (2.6 $\times$ 10$^9$ M$_\odot$) (Schödel et al. 2002).
(Muno et al. 2004). We can therefore solve for the equilibrium temperature of the gas using equation (8). The temperature maintained in this process is given by

\[ T \approx V^{-4/3} \left( \frac{W}{n_e k} \right)^{2/3} \left( \frac{m_e}{\gamma k} \right)^{1/3}. \]  

(9)

If \( W = 10^{40} \text{ erg s}^{-1} \) within 20 pc, then \( T \approx 8 \text{ keV} \). 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 centre of the gas cloud. Furthermore, the energy absorption in a normal X-ray nebula is about \( 10^{30} \text{ erg s}^{-1} \), so that the temperature of the nebula is about \( 10^4 \text{ keV} \) order (Leahy, Zhang & Kwok 1994). In our model, the energy absorption is \( 10^{40} \text{ erg s}^{-1} \), which can maintain the temperature of the hard component at 8 keV.

### 3 TWO-TEMPERATURE COMPONENTS

When the gas particles are in thermal equilibrium, \( \Gamma(n_e, T) = \bar{\Lambda}(n_e, T) \),

\[ \Gamma(n_e, T) = \bar{\Lambda}(n_e, T), \]  

(10)

where \( n_e \) is the number density of the gas particles, \( \Gamma \) and \( \bar{\Lambda} \) 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 \( (n_e, T) \) satisfying equation (10). The criterion for stability of the solution is (Bowers & Deeming 1984):

\[ \frac{\partial}{\partial T} (\Gamma - \bar{\Lambda}) + \frac{\partial}{\partial \rho} (\Gamma - \bar{\Lambda}) \left( \frac{\partial \rho}{\partial T} \right)_P < 0, \]  

(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 \( (r \leq R \approx 20 \text{ pc}) \) is given by

\[ \Gamma \simeq \Gamma_\text{e} n_e \sum_i a_i \sigma_{bf,i}, \]  

(12)

where \( \Gamma_\text{e} \) is a constant that depends on the size of the region. The cooling rate of X-ray emitting hot gas by bremsstrahlung radiation is:

\[ \bar{\Lambda} \sim \bar{\Lambda}_0 n_e \sum_i a_i Z_i^2 e^{-2I_i/kT} T_i^{-1/2}, \]  

(13)

where \( \bar{\Lambda}_0 \) 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 \( r \approx 20 \text{ pc} \) 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 \( (\tau < 1) \) in a large fraction of the volume of the cloud, so that most of the bremsstrahlung photons can escape the gas cloud easily. When the hot-gas particles are in thermal equilibrium, \( \Gamma = \bar{\Lambda} \), and the pressure is given by

\[ P = P_0 \frac{T_i^{3/2}}{Z_i} \sum_i a_i Z_i^2 e^{-2I_i/kT_i}, \]  

(14)

where \( P_0 = (1 \text{ keV})^{1/2} kT_0 / \bar{\Lambda}_0 \) and \( T_{keV} = T_i / (1 \text{ keV}) \).

Fig. 2 shows the relation between \( P \) and \( T_i \) 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 \( T_i \). By putting the heating and cooling rates into equation (11), we get the criterion for stable solutions:

\[ \sum_i a_i \sigma_{bf,i} \left[ \sum_i a_i Z_i^2 e^{-\beta_i} \left( \frac{3}{2} - \beta_i \right) \right] \leq \sum_i \sigma_{bf,i} \left[ a_i - T_i \frac{d a_i}{d T_i} \right]. \]  

\[ \beta_i = 2I_i/kT_i. \]  

where \( \beta_i = 2I_i/kT_i \). 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 side of the inequality in equation (15), respectively. In Fig. 3, we plot \( A \sim B \) against \( T_e \) for two values of \( \mu \). When \( \mu = 3.2 \) and \( \mu = 6.9 \), \( 0.8 < T_e < 4 \text{ keV} \) and \( 1.8 < T_e < 8 \text{ keV} \) are unstable solutions, respectively, as \( A > B \) and \( 0 < \mu < 3.2 \). We also indicate the unstable regions in Fig. 3, and we notice that a two-temperature phase may exist with \( T_e \approx 8 \text{ keV} \) and \( T_c < 0.8 \text{ keV} \) 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 centre.

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 $kT \sim B^2_{\text{centre}}/8\pi n_g$. For $n_g \sim 0.1 \text{ cm}^{-3}$, $B_{\text{centre}} \sim 0.2 \text{ mG}$, $kT \sim 8 \text{ keV}$. 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 $m_s = 16–18 \text{ keV}$ in the Milky Way centre, 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. Recently, a constraint $m_s \geq 28 \text{ keV}$ is obtained using the Sloan Digital Sky Survey Lyman-α data if sterile neutrinos are the major component of dark matter (Viel et al. 2008). Nevertheless, 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.

In addition, our predicted range of $m_s$ is also compatible with data obtained recently by using the high-resolution HIRES (High Resolution Echelle Spectrometer) spectra ($m_s \geq 5.6 \text{ keV}$) (Viel et al. 2008). The heating rate in the Milky Way centre 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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REFERENCES

Schödel R. et al., 2002, Nat, 419, 694

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