OBSERVATIONAL EVIDENCES FOR THE EXISTENCE OF 17.4 keV DECAYING DEGENERATE STERILE NEUTRINOS NEAR THE GALACTIC CENTER

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ABSTRACT

We show that the existence of a degenerate halo of sterile neutrinos with rest mass of 17.4 keV near the Galactic center (GC) can account for the excess 8.7 keV emission observed by the Suzaku mission and the power needed (10^{40} \text{erg s}^{-1}) to maintain the high temperature of the hot gas (8 keV) near the GC. The required decay rate and mixing angle of the sterile neutrinos are $\Gamma \approx 10^{-19} \text{s}^{-1}$ and $\sin^2 2\theta \approx 10^{-3}$, respectively. These values are consistent with a low reheating temperature, which suppresses the production of sterile neutrinos, resulting in a small sterile neutrino density parameter ($\Omega_{\nu} < 10^{-8}$). They are also allowed by X-ray background data and the isotope experiment. The large mixing angle leads to the exciting possibility that a sterile–active neutrino oscillation may be visible in near future experiments.

Key words: Galaxy: center

1. INTRODUCTION

Recent results from Chandra indicate that soft ($\sim$0.8 keV) and hard ($\sim$8 keV) hot gas components exist within the inner 20 pc (the field of view of Chandra) of the Galactic center (GC; Park et al. 2003; Muno et al. 2004). The power needed to maintain the temperatures of the soft and hard components of the hot gas are $3 \times 10^{36}$ erg s$^{-1}$ and $10^{40}$ erg s$^{-1}$, respectively. The energy needed for the soft component can be explained by 1% of kinetic energy from one supernova occurring every 3000 years, which is reasonable in the GC (Muno et al. 2004). However, the energy needed for the hard component cannot be explained satisfactorily (Muno et al. 2004). Chan & Chu (2008) proposed that a decaying sterile neutrino halo existing near the GC can solve the problem. The photons emitted by the decays of the sterile neutrinos can heat up the surrounding gas, and the energy is subsequently transferred to the entire region even beyond 20 pc at the GC. The temperature gradient of the 8 keV hard component is very small ($dT/dr \sim 10^4 \text{ K pc}^{-1}$), and therefore it can extend far beyond 20 pc. For this scenario to account for the observational data, the sterile neutrino rest mass is required to be $m_{\nu_s} \approx 16 - 19$ keV (Chan & Chu 2008). Recently, the Suzaku X-ray mission has started to observe emission lines above 6 keV near the GC (Koyama et al. 2007; Nobukawa et al. 2010). The observed intensities of the emission lines, including Lya (7.0 keV), Ly$\beta$ (8.2 keV), and Ly$\gamma$ (8.7 keV), from Fe xxvi are $1.66^{+0.09}_{-0.11} \times 10^{-1} \text{ph cm}^{-2} \text{s}^{-1}$, $2.29^{+1.35}_{-1.29} \times 10^{-5} \text{ph cm}^{-2} \text{s}^{-1}$, and $1.77^{+0.62}_{-0.56} \times 10^{-5} \text{ph cm}^{-2} \text{s}^{-1}$, respectively (Koyama et al. 2007). Based on these results, Prokhorov & Silk (2010) find an excess of Ly$\gamma$ intensity of $(1.1 \pm 0.6) \times 10^{-5} \text{ph cm}^{-2} \text{s}^{-1}$, which cannot be explained by ionization and recombination processes. Prokhorov & Silk (2010) proposed that decaying sterile neutrinos can provide the excess 8.7 keV photons. As the emitted photon energy $E_\gamma \approx m_{\nu_s}/2$, the required $m_{\nu_s}$ is about 17 keV, which agrees with Chan & Chu’s (2008) prediction.

By using the observed excess intensity of 8.7 keV photons and the Navarro–Frenk–White (NFW) density profile with 21.5 kpc scaled length to model the sterile neutrino halo, which means that the sterile neutrinos are the dominant dark matter component, Prokhorov & Silk (2010) calculated the sterile neutrino decay rate and the mixing angle with active neutrinos to be $\Gamma = (9.0 \pm 4.8) \times 10^{-28} \text{s}^{-1}$ and $\sin^2 2\theta = (4.1 \pm 2.2) \times 10^{-12}$, respectively. However, there is no evidence that the density profile of the sterile neutrino halo behaves like the NFW profile. If the sterile neutrinos are degenerate, the size of the halo can be very small (radius $R_h < 1$ pc; Bilic et al. 2001; Chan & Chu 2007). In this article, we show that the existence of a degenerate halo of decaying sterile neutrinos can account for the high temperature of the hot gas near the GC and the excess 8.7 keV photons observed by Suzaku simultaneously. In this model, the optically dense gas clouds inside and nearby the sterile neutrino halo absorb most of the energy of the photons emitted by the decaying of the sterile neutrinos. The energy is then transferred to the surrounding gas clouds by conduction (mean free path $\sim 2$ pc). Since the optical depth is larger than 1, only a small portion of the decayed photons can escape from the GC and constitute the excess 8.7 keV emission. The calculated emission intensity from the decaying sterile neutrinos agrees with the observation as well as that required by Prokhorov & Silk (2010). In this scenario, the sterile neutrino decay rate $\Gamma \approx 10^{-19} \text{s}^{-1}$ and mixing angle $\sin^2 2\theta \sim 10^{-3}$, which are consistent with a low reheating temperature and suggest that sterile–active neutrino oscillation may be visible in near future experiments.

2. THE DEGENERATE STERILE NEUTRINO HALO MODEL

Sterile neutrinos may decay into active neutrinos and photons ($\nu_s \rightarrow \nu_a + \gamma$). The energy of the photons is assumed to be $E_\gamma = 8.7$ keV. Therefore, $m_{\nu_s} \approx 2E_\gamma = 17.4$ keV. Since the size of a degenerate sterile neutrino halo with total mass $M_s \leq 10^6 M_\odot$ and $m_{\nu_s} \approx 17$ keV is much smaller than 20 pc, the total energy flux of the decayed photons within the field of view of Suzaku (solid angle $\Omega$) is given by (Nobukawa et al. 2010)

$$F_\gamma = \int_{4\pi r_0^2} \frac{P}{4\pi r_0^2} d\Omega \approx 2 \times 10^{-11} \text{erg cm}^{-2} \text{s}^{-1},$$

where $r_0 = 8.5$ kpc is the distance to the GC and $P = M_s \Gamma c^2/2 \approx 10^{40}$ erg s$^{-1}$ is the total power emitted in the sterile neutrino decays (the required power of the hard component
of the hot gas near GC). The excess energy flux observed by Suzaku is \( F_\gamma = (1.1 \pm 0.6) \times 10^{-5} E_\gamma \approx (1.5 \pm 0.8) \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} \). Therefore, only around 1% of photons can escape from the GC, and most of the emitted photons are first absorbed by the gas clouds inside the sterile neutrino halo and nearby. The optical depth \( \tau \) is given by

\[
\tau = \int \sum_i n_i \sigma_i dr,
\]

where \( \sigma_i \) is the effective absorption cross-section of 8.7 keV photons by different gas components including cold molecular hydrogen gas (i = H2), warm atomic gas (i = H, He), hot ionized gas (i = hot), and very hot ionized gas (i = vhot), and \( n_i \) is the number density of the gas components. Assuming all the gas components follow the same density profile near the GC, which can be modeled by \( n_i = \frac{n_{0,i}}{(1 + r/r_i)^{3/2}} \),

\[
\tau \approx 1.25 \sum_i n_i \sigma_i r_i \approx 4.3 \pm 0.6.
\]

Therefore, the observed 8.7 keV photon flux should be

\[
F'_\gamma = F_\gamma e^{-\tau} = (3.2 \pm 1.7) \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1},
\]

which is consistent with the observational data \( F'_\gamma = (1.5 \pm 0.8) \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} \). The corresponding column density is greater than \( 10^{23} \text{ cm}^{-2} \). This result is comparable with the column density of the gas clouds obtained nearby the GC. For example, Muno et al. (2004) and Murakami et al. (2000) indicate that the column density of the molecular clouds near the GC can be as large as \( 5 \times 10^{23} \text{ cm}^{-2} \) and \( 10^{24} \text{ cm}^{-2} \), respectively.

The high cooling rates of the atomic and molecular clouds suppress the temperature increase due to the intense X-ray.

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1 The effective cross-sections of hot gas and very hot gas depend on the metallicity of the hot gas. The metallicities of Si, S, and Fe in the interstellar medium are 1.13, 2.06, and 0.71 of solar metallicity, respectively (Muno et al. 2004). The metallicity of other metal ions is assumed to be 2–3 of solar metallicity (Sakano et al. 2004).

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2 Consider the H clouds (~10,000 K) and H2 molecular clouds (~1000 K), their cooling rates are \( \sim 10^{-22} \text{ erg cm}^{-3} \text{ s}^{-1} \) and \( \sim 10^{-21} \text{ erg cm}^{-3} \text{ molecule}^{-1} \text{ s}^{-1} \), respectively (McKee & Cowie 1977; Hollenbach & McKee 1979). Within 20 pc, the total cooling rates for the atomic and molecular clouds are both \( \sim 10^{31} \text{ erg s}^{-1} \), which is greater than the heating rate \( \sim 10^{30} \text{ erg s}^{-1} \). Therefore, the temperature of the atomic and molecular clouds can be kept lower than 10,000 K and 1000 K, respectively.

Observational data on stars S1 and S2 near the GC constrain \( M_\odot \) to be less than or equal to \( 2 \times 10^{5} M_\odot \) (Schödel et al. 2002). Since in our model the sterile neutrino decays also supply the energy needed for the hard component of the hot gas near the GC, \( M_\odot c^2/2 = 10^{40} \text{ erg s}^{-1} \), we have \( \Gamma > 5 \times 10^{-20} \text{ s}^{-1} \), which coincides with what is needed to solve the cooling flow problem in galaxy clusters (Chan & Chu 2007). The mixing angle of the sterile neutrinos is given by (Barger et al. 1995)

\[
\sin^2 2\theta = 1 - 10^{-3} \left( \frac{\Gamma}{2 \times 10^{-19} \text{ s}^{-1}} \right) \left( \frac{m_s}{17.4 \text{ keV}} \right)^{-5}.
\]

In our model, the mixing angle is \( \sin^2 2\theta \sim 10^{-3} \) to \( 10^{-4} \), which seems to disagree with the standard non-resonant production mechanism (Dodelson & Widrow 1994). Nevertheless, in the low reheating temperature scenario, the number density of active neutrinos is lower and the mixing angle can be much larger than the standard prediction (Giudice et al. 2001). Gelmini et al. (2004) proposed that if the reheating temperature is lower than 5 MeV, the mixing angle can be as large as \( \sin^2 2\theta \sim 10^{-3} \), which is consistent with our results. With such a large mixing angle, the sterile–active neutrino oscillation may be visible in future experiments (Gelmini et al. 2004; Yaguna 2007).

The large mixing angle of sterile neutrinos also implies a large decay rate. The total decay rate \( \Gamma_\gamma \) can be as large as \( 10^{21} \text{ s}^{-1} \) (see footnote 2). The current lower bound of the reheating temperature is \( T_R = 1 \text{ MeV} \) (Kohri et al. 2009). By using Gelmini et al.’s (2004) model and Equation (6), including the decay factor \( e^{-\Gamma_\gamma r} \) and the correction factor for \( T_R \approx 5 \text{ MeV} \) (Giudice et al. 2001), the present cosmological density parameter for \( m_s = 17.4 \text{ keV} \) is

\[
\Omega_\gamma \approx 0.039 \left( \frac{\sin^2 2\theta}{10^{-3}} \right) e^{-11000 \sin^2 2\theta}.
\]

The empirical upper limit of a recent X-ray background analysis of HEAO-1 and XMM-Newton data for \( m_s = 17.4 \text{ keV} \) is (Boyarsky et al. 2006)

\[
\Omega_\gamma \sin^2 2\theta < 1.9 \times 10^{-11}.
\]

The most conservative upper bound on \( \sin^2 2\theta \) from isotope experiments is \( \sin^2 2\theta < 3 \times 10^{-3} \) (Wietfeldt & Norman 1996). Therefore, we can plot the allowed region of \( \Omega_\gamma \) and \( \sin^2 2\theta \), which is shown in Figure 1. The allowed range is \( 1.3 \times 10^{-3} \leq \sin^2 2\theta \leq 3 \times 10^{-3} \). This range of mixing angle is consistent with our result and compatible with the recent X-ray background analysis. However, the sterile neutrinos, with density parameter \( \Omega_\gamma < 10^{-8} \) are only a minor component of cosmological dark matter. Since \( \sin^2 2\theta > 1.3 \times 10^{-3} \), the
The present mass of the sterile neutrino halo is $< 4 \times 10^4 M_\odot$. The original mass of the sterile neutrino halo before any significant decay can be as large as $7 \times 10^{10} M_\odot$. Nevertheless, this mass is still much less than the present total mass of dark matter in the Milky Way, which can be greater than $1.9 \times 10^{12} M_\odot$ (Carroll & Ostlie 2007).

3. SUMMARY

We have shown that the excess 8.7 keV emission observed by the *Suzaku* X-ray mission as well as the high temperature (~8 keV) of the hot gas near the GC both can be accounted for by the existence of a halo of degenerate decaying sterile neutrinos with 17.4 keV rest mass. The emitted photons from the sterile neutrino halo hiding deeply at the GC heat up the surrounding gas. The energy is then transferred to the nearby gas clouds to maintain their temperature at around 8 keV. The calculated photon flux for 8.7 keV photons from the GC is $F'_s = (3.2 \pm 1.7) \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$, which is consistent with the observed flux $F'_s = (1.5 \pm 0.8) \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$.

In this scenario, the decay rate and mixing angle of the sterile neutrinos are given by $\Gamma \geq 10^{-19}$ s$^{-1}$ and $\sin^2 2\theta \sim 10^{-3}$, respectively. These values are also consistent with those needed to account for the cooling flow problem in galaxy clusters (Chan & Chu 2007) and are consistent with the low reheating temperature model (Gelmini et al. 2004; Gelmini 2005). They are also allowed by bounds from X-ray background data and isotope experiment. The relatively large mixing angle suggests that sterile neutrinos may be directly studied in lab experiments in the near future, making it a particularly exciting candidate of warm dark matter particles.

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REFERENCES

Barger, V., Phillips, R. J. N., & Sarkar, S. 1995, Phys. Lett. B, 352, 365
Bilic, N., Lindebaum, R. J., Tupper, G. B., & Viollier, R. D. 2001, Phys. Lett. B, 515, 105
Boyarsky, A., Neronov, A., Ruchayskiy, O., & Shaposhnikov, M. 2006, MNRAS, 370, 213
Carroll, B. W., & Ostlie, D. A. 2007, An Introduction to Modern Astrophysics (San Francisco, CA: Pearson)
Chan, M. H., & Chu, M.-C. 2007, ApJ, 658, 859
Chan, M. H., & Chu, M.-C. 2008, MNRAS, 389, 297
Daltabuit, E., & Cox, D. P. 1972, ApJ, 177, 855
Dodelson, S., & Widrow, L. M. 1994, Phys. Rev. Lett., 72, 17
Ferriere, K., Gillard, W., & Jean, P. 2007, A&A, 467, 611
Ferriere, K. M. 2001, Rev. Mod. Phys., 73, 1031
Gelmini, G. 2005, Int. J. Mod. Phys. A, 20, 4670
Gelmini, G., Palomares-Ruiz, S., & Pascoli, S. 2004, Phys. Rev. Lett., 93, 081302
Giudice, G. F., Kolb, E. W., Riotto, A., Semikoz, D. V., & Tkachev, I. I. 2001, Phys. Rev. D, 64, 035012
Hollenbach, D., & McKee, C. F. 1979, ApJS, 41, 555
Kohri, K., Mazumdar, A., & Sahu, N. 2009, Phys. Rev. D, 80, 103504
Koyama, K., et al. 2007, PASJ, 59, 245
McKee, C. F., & Cowie, L. L. 1977, ApJ, 215, 213
Muno, M. P., et al. 2004, ApJ, 613, 326
Murakami, H., Koyama, K., Sakano, M., Tsujimoto, M., & Maeda, Y. 2000, ApJ, 534, 283
Nobukawa, M., Koyama, K., Tsuru, T. G., Ryu, S. G., & Tatischeff, V. 2010, PASJ, 62, 423
Park, S., Muno, M. P., Baganooff, F. K., Maeda, Y., Morris, M., Howard, C., Bautz, M. W., & Garmire, G. P. 2003, ApJ, 603, 548
Prokhorov, D. A., & Silk, J. 2010, ApJ, 725, L121
Sakano, M., Warwick, R. S., Decourchelle, A., & Predehl, P. 2004, MNRAS, 350, 129
Schödel, R., et al. 2002, Nature, 419, 694
Wientfeldt, F. E., & Norman, E. B. 1996, Phys. Rep., 273, 149
Yaguna, C. E. 2007, J. High Energy Phys., JHEP06(2007)002
Yan, M., Sadeghpour, H. R., & Dalgarno, A. 1998, ApJ, 496, 1044