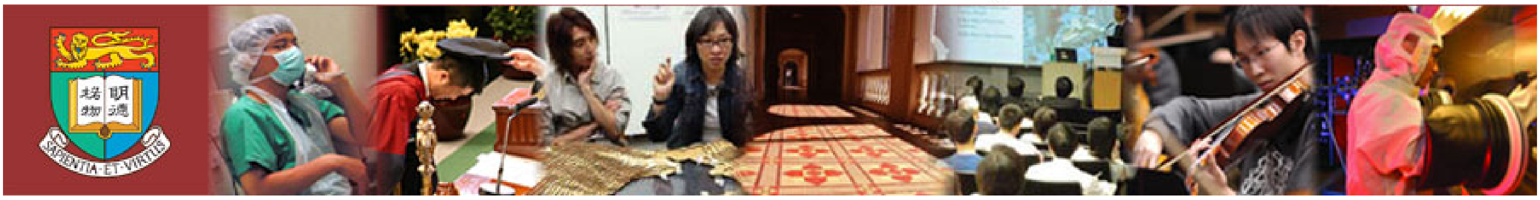

Title	**The Origin of the 6.4 keV Line Emission and H2 Ionization in the Diffuse Molecular Gas of the Galactic Center Region**
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THE ORIGIN OF THE 6.4 keV LINE EMISSION AND H_2 IONIZATION IN THE DIFFUSE MOLECULAR GAS OF THE GALACTIC CENTER REGION

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ABSTRACT

We investigate the origin of the diffuse 6.4 keV line emission recently detected by *Suzaku* and the source of H_2 ionization in the diffuse molecular gas of the Galactic center (GC) region. We show that Fe atoms and H_2 molecules in the diffuse interstellar medium of the GC are not ionized by the same particles. The Fe atoms are most likely ionized by X-ray photons emitted by Sgr A* during a previous period of flaring activity of the supermassive black hole. The measured longitudinal intensity distribution of the diffuse 6.4 keV line emission is best explained if the past activity of Sgr A* lasted at least several hundred years and released a mean 2–100 keV luminosity $\gtrsim 10^{38}$ erg s^{-1}. The H_2 molecules of the diffuse gas cannot be ionized by photons from Sgr A*, because soft photons are strongly absorbed in the interstellar gas around the central black hole. The molecular hydrogen in the GC region is most likely ionized by low-energy cosmic rays, probably protons rather than electrons, whose contribution into the diffuse 6.4 keV line emission is negligible.

Key words: cosmic rays – Galaxy: center – ISM: clouds – line: formation – X-rays: ISM

1. INTRODUCTION

The central molecular zone (CMZ) has long been known as a thin layer of about 300 × 50 pc in size, containing a total of $2.4 \times 10^7 M_\odot$ of dense ($n \sim 10^4$ cm^{-3}), high filling factor ($f > 0.1$) molecular material orbiting the Galactic center (GC) (see the review of Ferrière et al. 2007; Ferrière 2012). This canonical picture was drastically changed after the discovery of H_3^+ absorption lines generated by ionization of H_2 molecules. Observations by McCall et al. (2002) and Oka et al. (2005) showed that H_3^+ are mainly generated in diffuse ($n \sim 10^2$ cm^{-3}) clouds, where the ratio of H_3^+ to molecular hydrogen abundance is 10 times higher than in dense clouds. This diffuse gas has a high filling factor ($f_V \sim 0.3$), an unusually high temperature ($T_H \sim 250$ K), and a high and almost uniform ionization rate ($\zeta_2 \sim (1–3) \times 10^{-15}$ s^{-1}) throughout the CMZ (see Geballe 2012, and references therein). The source of this gas ionization is still debated.

Neutral Fe Kα line emission at 6.4 keV is observed from several dense GC molecular clouds. Detections of time variability of the X-ray emission from Sgr B2 (see, e.g., Inui et al. 2009; Nobukawa et al. 2011) and from several clouds within 15′ to the east of Sgr A* (Muno et al. 2007; Ponti et al. 2010), strongly suggest that the Fe Kα line emission from these regions is a fluorescence radiation excited by a past X-ray flare from the supermassive black hole. In this model, the variability of the line flux results from the propagation of an X-ray light front emitted by Sgr A* more than ∼100 yr ago.

The neutral Fe Kα line can also be generated by charged particles (see Dogiel et al. 1998; Valinia et al. 2000), and observations do not exclude that the 6.4 keV emission from some of GC clouds is produced by cosmic-ray (CR) electrons or protons and nuclei (see, e.g., Fukuoka et al. 2009; Capelli et al. 2011; Tatischeff et al. 2012; Yusef-Zadeh et al. 2002, 2013; Dogiel et al. 2009a, 2011).

In addition to the bright X-ray emission from dense clouds, Uchiyama et al. (2013) recently found with *Suzaku* diffuse emission at 6.4 keV from an extended region of the GC region, with a scale length in longitude of $\ell \sim 0^\circ.6$ and an extent in latitude of $b \sim 0^\circ.2$–$0^\circ.4$ when all known contributions from point sources and compact clouds ($n \gg 10^2$ cm^{-3}) were subtracted. These authors concluded that this emission is truly diffuse. Based on the equivalent width of the line (∼460 eV), they also concluded that the origin of the Fe I Kα line emission from the diffuse gas in the GC might be different from that of the dense clouds. However, Heard & Warwick (2013) recently suggested that unresolved stellar sources may make an important contribution to the observed diffuse emission at 6.4 keV.

We investigate in this paper if the diffuse 6.4 keV line emission and the H_3^+ absorption lines from the diffuse molecular gas ($n \sim 10^2$ cm^{-3}, i.e., outside dense clouds) can have the same origin, i.e., if Fe atoms and H_2 molecules in this medium can be ionized by the same particles. In this investigation, we obtain new constraints on the past X-ray flaring activity of Sgr A*, as well as on the density of low-energy cosmic rays (LECRs) in the GC region.

2. H_2 IONIZATION AND 6.4 keV LINE EMISSION FROM COSMIC RAYS

The ratio of the number of 6.4 keV photons and H_2 ionization produced by CRs of type i (electrons or protons) propagating in diffuse molecular gas can be estimated from

$$X_{6.4,i} \approx \frac{\eta_{\rm Fe}}{f_{\rm H_2}} \frac{\int_{I({\rm FeK})}^{E_{\rm max}} N_i(E)\sigma_{i{\rm Fe}}^{{\rm K}\alpha}(E) v_i(E) dE}{\int_{I({\rm H_2})}^{E_{\rm max}} N_i(E)\sigma_{i{\rm H_2}}^{\rm ioni}(E) v_i(E) dE}, \quad (1)$$

where $I({\rm FeK}) = 7.1$ keV and $I({\rm H_2}) = 15.6$ eV are the ionization potentials of the K shell of Fe and of H_2, respectively, $\eta_{\rm Fe}$ is the Fe abundance, $f_{\rm H_2} = n({\rm H_2})/(2n({\rm H_2}) + n({\rm H}))$ is the fractional density of H_2 molecules relative to the total number of H atoms, $N_i(E)$ is the differential equilibrium number of CRs of type i propagating in the diffuse gas, $v_i(E)$ is the velocity of

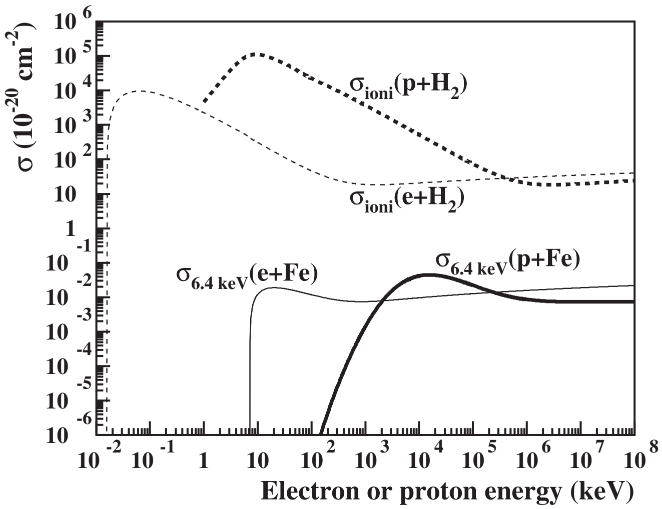

Figure 1. Cross sections involved in the calculation of the 6.4 keV photon yield per H_2 ionization in the CR model. Solid lines: cross sections for producing the 6.4 keV line by interaction of fast electrons (thin line) and protons (thick line) with Fe atoms. Dashed lines: H_2 ionization cross sections for impact of electrons (thin line) and protons (thick line).

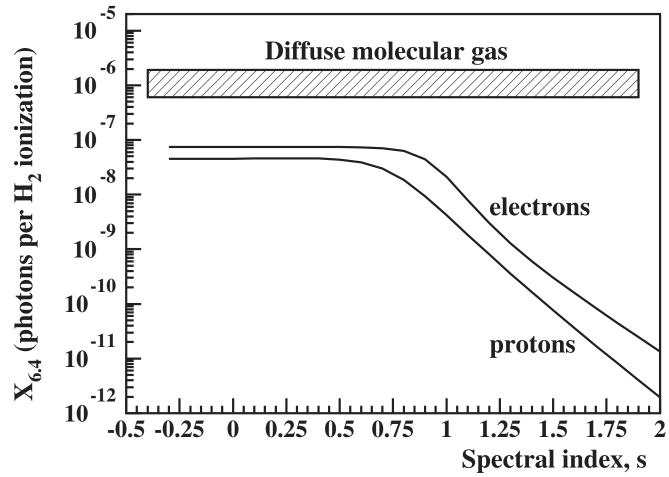

Figure 2. 6.4 keV photon yield per H_2 ionization in diffuse molecular gas. Theoretical values obtained from Equation (1) are compared with the range deduced from X-ray and H_3^+ observations, assuming $\langle n_{H_2}\rangle = 50$ cm^{-3} and $R = 200$ pc (Equation (3)). We used for the calculations $\eta_{Fe} = 6.9 \times 10^{-5}$, which is twice the solar abundance (Asplund et al. 2009), and $f_{H_2} = 0.5$, i.e., $n(H_2) \gg n(H)$.

these particles, E_{max} is their maximum kinetic energy, $\sigma_{i\rm Fe}^{K\alpha}(E)$ is the cross section for producing the 6.4 keV line by interaction of fast particles of type i with Fe atoms, and $\sigma_{iH_2}^{\rm ioni}(E)$ is the cross section for ionization of the H_2 molecule by the particle i. We have neglected in this equation the contribution of secondary electrons for both 6.4 keV line production and H_2 ionization.

The cross sections $\sigma_{i\rm Fe}^{K\alpha}$ and $\sigma_{iH_2}^{\rm ioni}$ are shown in Figure 1 for both CR electrons and protons. The H_2 ionization cross sections were taken from Padovani et al. (2009). In addition to the CR impact ionization reaction $i + H_2 \rightarrow i + H_2^+ + e^-$, the proton cross section $\sigma_{pH_2}^{\rm ioni}$ includes the charge-exchange process $p + H_2 \rightarrow H + H_2^+$, which is dominant below ∼40 keV (see Padovani et al. 2009; Figure 1). The cross sections $\sigma_{e\rm Fe}^{K\alpha}$ and $\sigma_{p\rm Fe}^{K\alpha}$ were calculated as in Tatischeff et al. (2012). We see that the H_2 ionization cross sections are much higher than that for the X-ray line production. At relativistic energies, the difference is by a factor ∼2000 for electrons and ∼3000 for protons.

The propagated CR spectrum $N_i(E)$ could be calculated in the framework of a given model for the source of these particles. Here instead, for the sake of generality, we use a simple power law in kinetic energy, $N_i(E) \propto E^{-s}$, allowing the spectral index s to take any value within a reasonable range. Calculated values of $X_{6.4,i}$ are shown in Figure 2 as a function of s.

Also shown in this figure is the 6.4 keV photon yield per H_2 ionization deduced from observations. The latter is estimated by assuming that the diffuse 6.4 keV line emission is emitted from a thick disk centered on Sgr A*, with volume $V = \pi R^2 h$ and solid angle at the observer position $\Omega = 2Rh/D^2$ (R and h are the disk radius and height perpendicular to the Galactic plane, respectively, and D is the distance to the GC):

$$X_{6.4} = \frac{4\pi D^2 I_{6.4}\Omega}{V\langle n_{H_2}\rangle \zeta_2}. \quad (2)$$

Here, $I_{6.4} = (7.3 \pm 0.7)$ photons cm^{-2} s^{-1} sr^{-1} is the measured intensity of the diffuse Fe Kα line emission near Sgr A* (Uchiyama et al. 2013), $\zeta_2 \approx (1\text{–}3) \times 10^{-15}$ s^{-1} is the estimated ionization rate of the H_2 molecule in the diffuse molecular gas (Goto et al. 2008), and $\langle n_{H_2}\rangle$ is the mean density in the disk of H_2 molecules of the diffuse gas ($\langle n_{H_2}\rangle = f_V n_{H_2}$, where f_V is the volume filling factor of the diffuse molecular gas and n_{H_2} is the H_2 number density in this gaseous component). We then get

$$X_{6.4} = \frac{8 I_{6.4}}{\langle n_{H_2}\rangle \zeta_2 R} \approx (0.6\text{–}1.9) \times 10^{-6} \times \left(\frac{\langle n_{H_2}\rangle}{50\ \rm cm^{-3}}\right)^{-1} \left(\frac{R}{200\ \rm pc}\right)^{-1}. \quad (3)$$

We see in Figure 2 that the theoretical photon yield is almost constant for low values of s, which reflects the constancy of the cross section ratio $\sigma_{i\rm Fe}^{K\alpha}/\sigma_{iH_2}^{\rm ioni}$ at relativistic energies (Figure 1). The calculated photon yield amounts to $\lesssim$10% of the measured value at low s and rapidly declines for $s \gtrsim 0.75$.

Yusef-Zadeh et al. (2013) estimated that a population of LECR electrons responsible for the ionization of the diffuse H_2 gas would contribute to ∼10% of the diffuse 6.4 keV line emission detected by *Suzaku*, which is consistent with the maximum contribution we expect for a hard electron spectrum (see Figure 2). These authors also suggested that the remaining 90% of the X-ray emission is produced by interactions of electrons with a denser ($n \sim 10^3$ cm^{-3}) molecular gas. But this would imply the existence of a massive ($\sim 10^7\ M_\odot$) molecular gas component with a high ionization rate ($\zeta_2 \gtrsim 10^{-14}$ s^{-1}), which should have been detected with H_3^+ observations (see, e.g., Geballe 2012). Independent of the exact density of the diffuse molecular gas, the comparison of the cross sections $\sigma_{i\rm Fe}^{K\alpha}$ and $\sigma_{iH_2}^{\rm ioni}$ (Figure 1) shows that the bulk of the diffuse 6.4 keV line emission is not produced by CRs.

3. THE ORIGIN OF THE DIFFUSE 6.4 keV LINE EMISSION: PAST FLARING ACTIVITY OF SGR A*

Unlike the 6.4 keV line emission from dense clouds, the X-ray fluorescence emission from the diffuse gas is predicted to be almost constant for several hundred years, which is the time needed for a photon to cross the CMZ (see Chernyshov et al. 2012). We use here for the gaseous disk radius $R = 200$ pc.

The expected flux in the 6.4 keV line depends on two parameters of the flare from Sgr A*: its luminosity L_X and

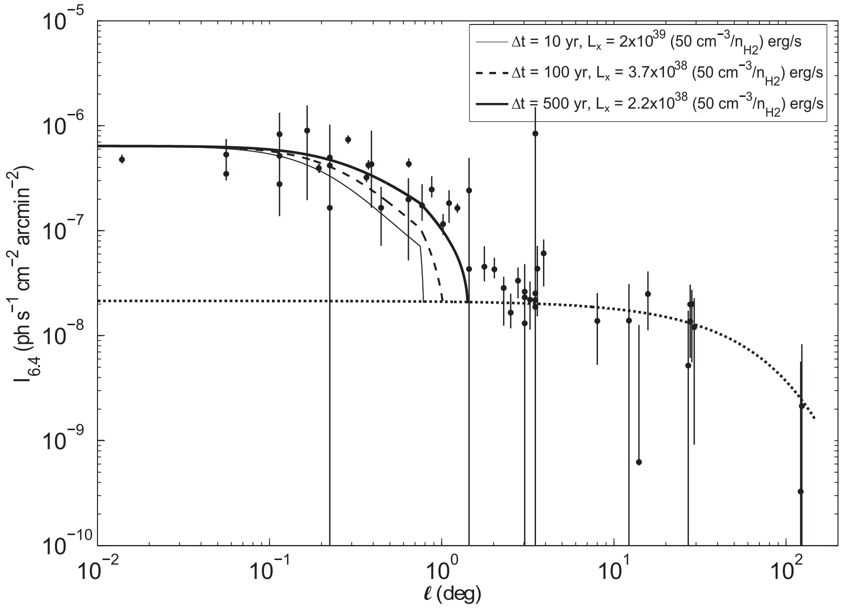

Figure 3. Longitudinal distribution of the 6.4 keV line generated by primary photons in the GC region calculated for the Fe abundance $\eta_{\rm Fe} = 6.9 \times 10^{-5}$, which is twice the solar abundance. The data points are from Uchiyama et al. (2013). The modeled emission from the Galactic ridge (dotted line) is also from that paper.

duration Δt. The flare duration estimated from observations ranges from $\sim$10 yr (see Yu et al. 2011) to 500 yr (Ryu et al. 2013). The flare probably ended at $T \sim$ 70–150 yr ago (see, e.g., Ponti et al. 2010; Ryu et al. 2013). The required luminosity L_X in a given energy range $E_{\rm min} - E_{\rm max}$ can be estimated for each value of Δt from the observed intensity of diffuse 6.4 keV line emission.

As Koyama et al. (2009) and Terrier et al. (2010) showed, the differential spectrum of primary X-ray photons emitted by Sgr A* can be described by a power law in the 2–100 keV energy range:

$$n_{\rm ph}(E_X, r = 0) \propto E_X^{-2}. \tag{4}$$

The distribution of primary photons in the disk as a function of energy E_X and radius r is then given by

$$n_{\rm ph}(E_X, r) = \frac{Q_0}{4\pi c r^2 E_X^2} \exp(-\langle n_{\rm H_2}\rangle \sigma_{\rm abs}(E_X) r / f_{\rm H_2}) \times \theta(r - cT)\theta(cT + c\Delta t - r), \tag{5}$$

where $\theta(x)$ is the Heaviside function, $\sigma_{\rm abs}$ is the photoelectric absorption cross section per H atom (Balucinska-Church & McCammon 1992), c is the speed of light, and Q_0 is a normalization constant derived from the estimated luminosity of Sgr A* in the energy range $E_{\rm min} - E_{\rm max}$ (below we use the range 2–100 keV):

$$L_X = Q_0 \ln(E_{\rm max}/E_{\rm min}). \tag{6}$$

A distant observer sees at present the reflection of a light front emitted by Sgr A* at time t in the past as a parabola (see, e.g., Sunyaev & Churazov 1998),

$$\frac{z}{c} = \frac{1}{2t}\left[t^2 - \left(\frac{x}{c}\right)^2\right], \tag{7}$$

where the coordinates $x \simeq \ell D$ and z are perpendicular and along the line of sight, respectively. The observable longitudinal distribution of 6.4 keV line emission is then given by

$$I_{6.4}(\ell) = \frac{\eta_{\rm Fe}\langle n_{\rm H_2}\rangle}{4\pi f_{\rm H_2}} \int_{I({\rm FeK})}^{E_{\rm max}} \sigma_{X{\rm Fe}}^{{\rm K}\alpha}(E_X) \times \left(\int_{z_1}^{z_2} n_{\rm ph}[E_X, \sqrt{(\ell D)^2 + z^2}] dz\right) dE_X, \tag{8}$$

where z_1 and z_2 are calculated from Equation (7) for $t = T$ and $t = T + \Delta t$, respectively, and $\sigma_{X{\rm Fe}}^{{\rm K}\alpha}$ is the cross section for producing the 6.4 keV line by Fe K-shell photoionization (see Tatischeff 2003).

The results obtained for different values of Δt and L_X are shown in Figure 3, together with the *Suzaku* data (Uchiyama et al. 2013). The amount of illuminated diffuse gas depends on the flare duration. For $\Delta t = 10$ yr, the required luminosity of Sgr A* is about 10^{39} erg s^{-1}. But for $\Delta t \gtrsim 350$ yr most of the disk emits the Fe Kα line, whose brightness is then independent of the flare duration. The required X-ray luminosity in this case is about 10^{38} erg s^{-1}. We see in Figure 3 that the *Suzaku* data are in better agreement with the assumption of a long flare duration. The possibility of such a long period of activity with some sporadic flux variability is not excluded by observations of the Sgr C region (Ryu et al. 2013). However, *Chandra* observations of clouds within the central 30 pc reveal they are probably illuminated by two short flares (Clavel et al. 2013).

We also see in Figure 3 that even for $\Delta t = 500$ yr, the model slightly underestimates the measured 6.4 keV line flux at longitudinal distances from Sgr A* of $\sim 1°$. This suggests that the warm and diffuse gas extends beyond the CMZ, which might be already suggested by the measured outward movement of this gas component (see Geballe 2012).

4. THE ORIGIN OF THE H_2 IONIZATION IN THE DIFFUSE MOLECULAR GAS: X-RAY PHOTONS VERSUS LECRs

If the flare ended $\sim$100 yr ago, then soft photons emitted by Sgr A* were absorbed in the dense interstellar medium of the GC. For the hydrogen density $\sim$100 cm^{-3}, photons with energies $E_X > 1$ keV survive in this region. From the Compton echo, we know the spectral shape of primary photons of $E_X > 1$ keV emitted by Sgr A*: it is presented by Equation (4).

Because the ionization rate ζ_2 is expected to be strongly non-uniform, we calculate instead the H_3^+ column density, $N(H_3^+)$, which at the longitudinal distance ℓ from Sgr A* has the form

$$N(H_3^+) = \int_l n_{H_3^+}(r, \tilde{t})dl. \quad (9)$$

Here, l is a trajectory of an IR photon through the disk diffuse gas and $n_{H_3^+}(r, \tilde{t})$ is the H_3^+ density in the disk as a function of radius r and time $\tilde{t}$, where the tilde indicates that IR photons crossing the gaseous disk interact with H_3^+ ions of different "ages." Therefore, the geometrical formalism entering in the calculation of $N(H_3^+)$ (Equation (9)) is similar to that applied for $I_{6.4}(\ell)$ (Equation (8)).

The process of H_2 photoionization leading to H_3^+ production is time variable (see, e.g., Goto et al. 2013):

$$\frac{\partial n_{H_3^+}}{\partial t} = \zeta_2(r, t)\langle n_{H_2}\rangle - \langle v_e\sigma^{\rm rec}_{H_3^+}\rangle n_e n_{H_3^+}, \quad (10)$$

where $\langle v_e\sigma^{\rm rec}_{H_3^+}\rangle$ is the rate of H_3^+ dissociative recombination and n_e is the density of free electrons. The ionization rate is due to both photoelectric ionization and Compton scattering:

$$\zeta_2(r, t) \simeq \int_{I(H_2)}^{E_{\rm max}} dE_X\sigma^{\rm ioni}_{XH_2}(E_X)cn_{\rm ph}(E_X, r, t)M_{\rm sec}(E_X) + 2\int_{E_{\rm I}}^{E_{\rm max}} dE_X cn_{\rm ph}(E_X, r, t)\int_{I(H_2)}^{E_e^{\rm max}} dE_e\frac{d\sigma_c}{dE_e}M_{\rm sec}(E_e), \quad (11)$$

where $\sigma^{\rm ioni}_{XH_2}$ is the H_2 photoelectric ionization cross section (Yan et al. 2001), $d\sigma_c/dE_e$ is the Klein–Nishina differential cross section as a function of the energy of the recoil electron E_e, $M_{\rm sec}(E_e) = [E_e - I(H_2)]/W$ with $W \approx 40$ eV (see Dalgarno et al. 1999) being the mean multiplicity of H_2 ionization by a secondary electron, $E_{\rm I} \approx \sqrt{m_ec^2{\rm I}(H_2)/2}$ the minimum energy of an X-ray photon to ionize an H_2 molecule by Compton scattering, $E_e^{\rm max} = 2E_X^2/(m_ec^2 + 2E_X)$, and $n_{\rm ph}(E_X, r, t)$ is given by Equation (5).

The fraction of free electron can be approximated by the abundance of singly ionized carbon, C^+, assuming that nearly all free electrons are the result of C photoionization (see, e.g., Oka 2006). Here, the C abundance is taken to be twice that measured by Sofia et al. (2004) in the Galactic disk, i.e., $\eta_C = 3.2 \times 10^{-4}$.

The H_3^+ recombination rate is given in McCall et al. (2004) as a function of the gas temperature T_H in K:

$$\langle v_e\sigma^{\rm rec}_{XH_3^+}\rangle = -1.3 \times 10^{-8} + 1.27 \times 10^{-6}T_H^{-0.48}. \quad (12)$$

For $T_H \sim 250$ K, the rate is $\sim 8 \times 10^{-8}$ cm^3 s^{-1} and the characteristic recombination time $t_{\rm rec} = [n_e\langle v_e\sigma^{\rm rec}_{H_3^+}\rangle]^{-1} \sim 10$ yr, which is much smaller than the light propagation time across the CMZ.

The solution of Equation (10) takes the form

$$n(H_3^+) = \int_0^t d\tau \exp\left[\langle v_e\sigma^{\rm rec}_{H_3^+}\rangle n_e(\tau - t)\right]\zeta_2(r, \tau)\langle n_{H_2}\rangle. \quad (13)$$

Absorption of low-energy photons in the dense material surrounding Sgr A* (see Ferrière 2012) can be essential.

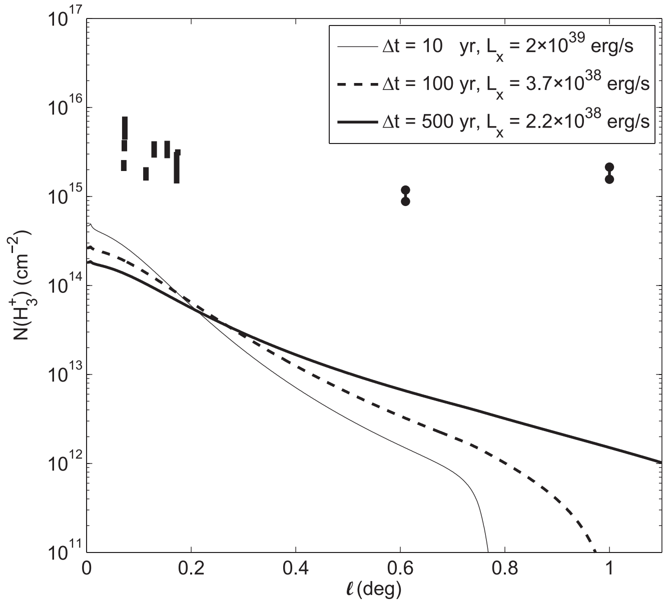

Figure 4. H_3^+ column density provided by primary photons from Sgr A*, for three values of $(\Delta t, L_X)$. The data points are from Goto et al. (2008, 2011).

However, to derive an upper limit on $N(H_3^+)$, we neglect here the photoabsorption in this dense medium and consider only that occurring in the diffuse molecular gas of mean density $\langle n_{H_2}\rangle = 50$ cm^{-3}. H_3^+ column densities calculated for $T = 100$ yr and for three values of $(\Delta t, L_X)$ are shown in Figure 4. We see that $N(H_3^+)$ is no more than 4×10^{14} cm^{-2}, which is less than the observed values, which lie in the range 10^{15}–10^{16} cm^{-2} (see Goto et al. 2008, 2011). Thus, although flare photons from Sgr A* probably generate most of the 6.4 keV line emission from the GC region, they are most likely not the main source of H_2 ionization in the diffuse gas.

Ionization of molecular hydrogen can be effectively produced by LECRs. Yusef-Zadeh et al. (2013) suggest that the necessary ionization rate, $\zeta_2 \sim (1$–$3) \times 10^{-15}$ s^{-1}, can be provided by low-energy electrons ($E \gtrsim 100$ keV). These authors estimated the energy distribution of radio-emitting electrons ($E > 1$ GeV) in the GC region assuming for the mean magnetic field strength $B \sim 10^{-5}$ G, and then extrapolated the derived electron spectrum to lower energies. However, 100 keV electrons have a short lifetime in the diffuse molecular gas ($\sim$100 yr), which makes it difficult to explain the measured uniformity of the H_2 ionization rate, unless low-energy electrons are constantly produced all over the disk. Besides, if the magnetic field strength in the GC amounts to $B \gtrsim 5 \times 10^{-5}$ G as derived by Crocker et al. (2010), then the calculations of Yusef-Zadeh et al. (2013) would give $\zeta_2 \lesssim 10^{-16}$ s^{-1}. We also note that the inclusion of Coulomb energy losses in these calculations would flatten the spectrum of radio-emitting electrons at low energies, thus reducing the ionization rate.

For all of these reasons, molecular hydrogen in the diffuse gas is more likely to be ionized by subrelativistic protons. These particles can be generated either by star accretion onto the central black hole (Dogiel et al. 2009b) or by diffusive shock acceleration in supernova remnants (SNRs). The latter supply in the GC region a total kinetic power of $\sim 10^{40}$ erg s^{-1} (see Crocker et al. 2011). In comparison, the proton power needed to explain the H_2 ionization rate is $\dot{W}_p \sim \zeta_2\langle n_{H_2}\rangle VW \sim 2 \times 10^{39}$ erg s^{-1}, such that an efficiency of proton acceleration in SNRs of $\sim$20% could account for the H_3^+ line measurements.

5. CONCLUSIONS

We have shown that the diffuse 6.4 keV line radiation from the GC region is most likely produced by the hard X-ray photon emission from Sgr A* that also produces fluorescence X-ray radiation in several dense molecular clouds. The longitudinal intensity distribution of the diffuse Fe Kα line emission thus provides an additional constrain on the past activity of the central black hole. Our results on the past X-ray luminosity of Sgr A* are broadly consistent with that obtained from the 6.4 keV line radiation of dense clouds by Capelli et al. (2012), L_X(2–10 keV) $\sim 10^{38}$ erg s^{-1} if the flare duration was about 100 yr, and by Ponti et al. (2010), L_X(2–100 keV) $\sim 10^{39}$ erg s^{-1} if $\Delta t \sim 10$ yr. But the measured distribution of the diffuse 6.4 keV line emission strongly suggests that the past activity of Sgr A* lasted at least several hundred years with sporadic flux variabilities as follows from *Suzaku* observations of the Sgr C molecular cloud complex (Ryu et al. 2013). However, the overall agreement of our results on L_X with that previously obtained from the X-ray emission of dense molecular clouds suggests that most of the large-scale 6.4 keV line emission from the GC region is truly diffuse and not due to a collection of unresolved point sources.

On the other hand, high-energy photons emitted by Sgr A* are not responsible for the ionization of the diffuse molecular gas. The H_2 molecules in this gas are very likely ionized by LECRs, probably protons accelerated in SNRs, whose contribution into the diffuse 6.4 keV line emission is negligible.

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REFERENCES

Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, ARA&A, 47, 481
Balucinska-Church, M., & McCammon, D. 1992, ApJ, 400, 699
Capelli, R., Warwick, R. S., Porquet, D., et al. 2011, A&A, 530, 38
Capelli, R., Warwick, R. S., Porquet, D., et al. 2012, A&A, 545, 35
Chernyshov, D., Dogiel, V., Nobukawa, M., et al. 2012, PASJ, 64, 14
Clavel, M., et al. 2013, A&A, in press
Crocker, R. M., Jones, D. I., Aharonian, F., et al. 2011, MNRAS, 413, 763
Crocker, R. M., Jones, D. I., Melia, F. J., et al. 2010, Natur, 463, 65
Dalgarno, A., Yan, M., & Liu, W.-H. 1999, ApJS, 125, 237
Dogiel, V., Cheng, K.-S., Chernyshov, D., et al. 2009a, PASJ, 61, 901
Dogiel, V., Chernyshov, D., Koyama, K., et al. 2011, PASJ, 63, 535
Dogiel, V. A., Ichimura, A., Inoue, H., & Masai, K. 1998, PASJ, 50, 567
Dogiel, V. A., Tatischeff, V., Cheng, K. S., et al. 2009b, A&A, 508, 1
Ferrière, K. 2012, A&A, 540, 50
Ferrière, K., Gillard, W., & Jean, P. 2007, A&A, 467, 611
Fukuoka, R., Koyama, K., Ryu, S. G., & Tsuru Go, T. 2009, PASJ, 61, 593
Geballe, T. R. 2012, RSPTA, 370, 5151
Goto, M., Indriolo, N., Geballe, T. R., & Usuda, T. 2013, arXiv:1305.3915
Goto, M., Usuda, T., & Geballe, Th. R. 2011, PASJ, 63, L13
Goto, M., Usuda, T., Nagata, T., et al. 2008, ApJ, 688, 306
Heard, V., & Warwick, R. S. 2013, MNRAS, 428, 3462
Inui, T., Koyama, K., Matsumoto, H., & Tsuru Go, T. 2009, PASJ, 61, 241
Koyama, K., Takikawa, Y., Hyodo, Y., et al. 2009, PASJ, 61, S255
McCall, B. J., Hinkle, K. H., Geballe, T. R., et al. 2002, ApJ, 567, 391
McCall, B. J., Huneycutt, A. J., Saykally, R. J., et al. 2004, PhRvA, 70, 2716
Muno, M. P., Baganoff, F. K., Brandt, W. N., Park, S., & Morris, M. R. 2007, ApJL, 656, L69
Nobukawa, M., Ryu, S. G., Tsuru Go, T., & Koyama, K. 2011, ApJL, 739, L52
Oka, T. 2006, PNAS, 103, 12235
Oka, T., Geballe, Th. R., Goto, M., et al. 2005, ApJ, 632, 882
Padovani, M., Galli, D., & Glassgold, A. E. 2009, A&A, 501, 619
Ponti, G., Terrier, R., Goldwurm, A., et al. 2010, ApJ, 714, 732
Ryu, S. G., Nobukawa, M., Nakashima, S., et al. 2013, PASJ, 65, 33
Sofia, U. J., Lauroesch, J. T., Meyer, D. M., & Cartledge, S. I. B. 2004, ApJ, 605, 272
Sunyaev, R., & Churazov, E. 1998, MNRAS, 297, 1279
Tatischeff, V. 2003, in Final Stages of Stellar Evolution, EAS Publication Ser., Vol. 7, ed. C. Motch & J.-M. Hameury (Les Ulis, France: EDP Sciences), 79
Tatischeff, V., Decourchelle, A., & Maurin, G. 2012, A&A, 546, 88
Terrier, R., Ponti, G., Belanger, G., et al. 2010, ApJ, 719, 143
Uchiyama, H., Nobukawa, M., Tsuru Go, T., & Koyama, K. 2013, PASJ, 65, 19
Valinia, A., Tatischeff, V., Arnaud, K., et al. 2000, ApJ, 543, 733
Yan, M., Sadeghpour, H. R., & Dalgarno, A. 2001, ApJ, 559, 1194
Yu, Y.-W., Cheng, K.-S., Chernyshov, D. O., & Dogiel, V. A. 2011, MNRAS, 411, 2002
Yusef-Zadeh, F., Hewitt, J. W., Wardle, M., et al. 2013, ApJ, 762, 33
Yusef-Zadeh, F., Law, C., & Wardle, M. 2002, ApJL, 568, L121