Spatial and Temporal Variations of the Diffuse Iron 6.4 keV Line in the Galactic Center Region

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Abstract

We analyze the diffuse Fe I K\(\alpha\) line generated in the diffuse interstellar molecular hydrogen by primary photons or subrelativistic protons injected by Sagittarius (Sgr) A\(\ast\). We showed that unlike emission from compact molecular clouds, this emission can be permanently observed in the directions of the Galactic center. We conclude that the diffuse emission of 6.4 keV line observed at present is probably due to Fe I K\(\alpha\) vacancy production by primary photons if the X-ray luminosity of Sgr A\(\ast\) was about \(L_X \sim 10^{39} - 10^{40}\) erg s\(^{-1}\). In principle these data can also be described in the framework of the model when the 6.4 keV line emission is generated by subrelativistic protons generated by accretion onto the central black hole but in this case extreme parameters of this model are necessary.

Key words: Galaxy: center — X-rays: ISM — cosmic-rays
1. Introduction

Detection of the Fe\textsc{i} K\textalpha{} (6.4 keV) line from molecular clouds in the Galactic center (GC) is one of the most remarkable events in the high energy astrophysics of the last decades. The story had started from 1993 when Sunyaev et al. (1993) found a diffuse X-ray emission from compact sources in the GC. They interpreted this emission as due to reflection of photons by dense molecular clouds (Compton echo) which were irradiated by a nearby X-ray source. In addition, they predicted a bright fluorescent K\textalpha{} line in the scattered spectrum of the clouds due to the K-absorption of photons with energies $E > 7.1$ keV. This line was indeed discovered soon afterwards by Koyama et al. (1996). The brightest region of the 6.4 keV emission was located over the giant molecular cloud Sgr B2. Later on the 6.4 keV emission was discovered also in other molecular clouds of the GC (see Murakami et al. 2001; Nobukawa et al. 2008; Bamba et al. 2009).

1.1. X-ray Reflection Nebula (XRN) model

Koyama et al. (1996) (see also Murakami et al. 2000) speculated that the 6.4 keV flux from Sgr B2 is due to the past activity of the the Galactic nucleus Sgr A* which had been bright several hundred years ago but is currently dim. From the observed flux of 6.4 keV photons from the cloud, $F_{6.4} \sim 10^{-4}$ ph cm$^{-2}$ s$^{-1}$, and the gas column density of the cloud the differential spectrum of primary photons $dn(E_x)/dE_x$ can be estimated from the equation (see e.g. Tatischeff 2003)

$$F_{6.4} \sim \frac{c}{4\pi R_{\odot}^2} \int d^3r \int_{E_x > 7.1 \text{ keV}} n_H(r) \frac{dn(E_x,r)}{dE_x} dE_x \varepsilon(E_x, r) dE_x$$

where $V_{\text{Sgr B2}}$ is the volume of the cloud, $\varepsilon(E_x, r)$ is the emissivity of 6.4 keV photons at the coordinate $r$ inside the cloud and $R_{\odot}$ is the distance to Earth. The spectrum of primary photons can be derived from the observed continuum emission from Sgr B2 which in the case of the XRN scenario is the same as the spectrum of primary photons. Murakami et al. (2000) showed that these spectrum was a power-law with the spectral index of $-2$ in the energy range 2–10 keV (see also Koyama et al. 2009)

$$\frac{dn(E_x)}{dE_x} \propto E_x^{-2}.$$ (2)

The 2–10 keV luminosity of primary photons from Sgr A* necessary to produce the observed 6.4 keV emission from Sgr B2 was estimated by Murakami et al. (2000),

$$L_{2-10 \text{ keV}} \sim 3 \times 10^{39} \left( \frac{d}{100 \text{ pc}} \right)^2 \text{ erg s}^{-1}$$ (3)

where $d$ is the distance between Sgr A* and Sgr B2.

The most direct evidence to favor the photoionization by an X-ray flash of the central source would be a time variability of the 6.4 keV line emission from molecular clouds because of a relatively short time in which a photon crosses them. This idea about the Sgr A* past activity as the origin of 6.4 keV emission from Sgr B2 was confirmed recently. Observations found a steady decrease of the X-ray flux from Sgr B2 for the period $\lesssim 10$ years. Time variations of the emission are expected in the
XRN model and interpreted as photoionization of iron atoms by a flux of primary X-rays emitted by the central source Sgr A* due to an X-ray flare occurred there about 100–300 years ago (Koyama et al. 2008; Inui et al. 2009; Terrier et al. 2010; Nobukawa et al. 2011).

1.2. Alternative Models of 6.4 keV Line Emission

In principle a flux of the 6.4 keV line can also be generated by collisions of subrelativistic charged particles with the molecular gas in the GC. Thus, Yusef-Zadeh et al. (2002) accounted the impact of subrelativistic electrons with energies 10 – 100 keV from local sources with diffuse neutral gas producing both nonthermal bremsstrahlung X-ray continuum emission and diffuse 6.4 keV line emission. Dogiel et al. (2009a) suggested a scenario for the 6.4 keV line emission from molecular clouds which was excited by a flux of subrelativistic protons produced by star accretion onto the central black hole. Below these two scenarios are denoted as the low energy cosmic-ray electron model (LECRe) and the low energy cosmic-ray proton model (LECRp). We note that because of relatively long life time of protons in comparison with the average time of star capture the LECRp component of 6.4 keV line emission in the GC is quasi-stationary.

Generation of the 6.4 keV line is accompanied by a continuum X-ray emission produced by the Thomson scattering for the XRN scenario and by bremsstrahlung for the LECRe and LECRp models. Therefore the origin of 6.4 keV line flux from the clouds can be defined from the analysis of the equivalent width $eW$ of the iron line in the spectrum which is the ratio of the line flux to the continuum intensity at $E_x = 6.4$ keV,

$$eW = \frac{F_{6.4}}{F_x(E_x = 6.4 \text{ keV})}.$$  \hspace{1cm} (4)

The width is a function of the iron abundance $\eta$ in the clouds.

From estimations of $eW$ for the cloud Sgr B2 Nobukawa et al. (2010) concluded that the photoionization interpretation seemed to be more attractive in comparison with the electron impact scenario. The required abundance of iron in the cloud was estimated by Nobukawa et al. (2011) by the value $\eta = 1.3$ solar. However, Capelli et al. (2011) might find the iron line emission which was produced by subrelativistic particles. They presented results of eight years of XMM-Newton observations of the region surrounding the Arches cluster in the Galactic Center. They analyzed spatial distribution and temporal behavior of the 6.4 keV line emission and concluded that the origin of this emission might be of the photoionization origin, although excitation by cosmic-ray particles was not excluded. Moreover, they concluded that for the three clouds nearest to the Arches cluster, which showed a constant flux over the 8-year observation, the origin of the line as photoionization by photons from Sgr A* seemed to be at best tentative, and the hardness of the nonthermal component associated with the 6.4-keV line emission might be best explained in terms of bombardment by cosmic-ray particles.

Recent Suzaku observations might also find the iron line emission which was produced by subrelativistic particles (Fukuoka et al. 2009; Tsuru et al. 2010). For the clumps G 0.174–0.233 with
they concluded that the XRN scenario was favored. On the other hand, for the clump G 0.162−0.217 with $eW \simeq 200$ eV they assumed that the emission from there was due to low energy cosmic-ray electron (LECRE). They found also that the $eW$ of the 6.4 keV emission line detected in the X-ray faint region (non galactic molecular cloud region) was significantly lower than one expected in the XRN scenario but higher than that of the LECRe model.

Dogiel et al. (2011) showed that estimates of $eW$ alone did not allow to distinguish firmly between the XRN and LECR scenarios because in the latter case the value of $eW$ depended strongly on a spectral index of ionizing charged particles, especially if they were subrelativistic protons. In the case of ionization by charged particles spatial characteristics of 6.4 keV line are expected quite different for electrons and protons. While for electrons we expect rather local ionization of the medium because of their relatively short lifetime, protons can fill an extended region around the GC. If protons generate 6.4 keV line in the GC then at least two components of 6.4 keV line emission from the molecular clouds and the diffuse molecular gas can be generated there. The first one is a time variable component generated by a flare of primary X-rays emitted by Sgr A*, and the second is a quasi-stationary component produced by subrelativistic protons interacting with the gas.

Observations of the 6.4 keV flux from Sgr B2 have not found up to now any evident stationary component for the GC molecular clouds, though as predicted by Ponti et al. (2010) a fast decrease of 6.4 keV emission observed with XMM-Newton for several molecular clouds suggested that the emission generated by low energy cosmic-rays, if present, might become dominant in several years. A component of another than that of the XRN origin may also be seen in the X-ray spectrum of faint molecular regions in the GC as follows from Fukuoka et al. (2009). Below we derive parameters of the diffuse 6.4 keV line emission in the framework of the XRN and LECRp models in attempts to define the origin of the observed diffuse line flux from the GC.

2. Diffuse Emission of the 6.4 keV Line from the GC

The intensity of the diffuse 6.4 keV line from the GC depends on parameters of the intercloud molecular gas there. The inner bulge (200–300 pc central region) contains $(7 - 9) \times 10^7$ $M_\odot$ of hydrogen gas. In spite of relatively small radius this region contains about 10% of the Galaxy’s molecular mass. Half of the molecular gas is contained in very compact clouds of mass $10^4 - 10^6 M_\odot$, average densities of which is $\geq 10^4$ cm$^{-3}$ with a volume filling factor of only a few per cent, then the cloud radius is in the range 1–40 pc. The other half forms the molecular intercloud gas with the densities of at least $n_H > 10 - 10^2$ cm$^{-3}$ (see Morris & Serabyn 1996). Launhardt et al. (2002) estimated for the inner $\sim 200$ pc region the averaged molecular hydrogen density $n_H$ to be 140 cm$^{-3}$ assuming homogeneous matter distribution, and for a thin intercloud medium $n_H \sim 10$ cm$^{-3}$.

Recently Koyama et al. (2009) provided careful analysis with high energy resolution and low background of the diffuse 6.4 keV emission and of the hard X-ray continuum associated with this line in the GC region. From the Suzaku data they estimated the continuum X-ray emission which is proportional to the intensity of diffuse 6.4 keV line.
More recently Uchiyama et al. (2011) provided a careful analysis of 6.4 keV emission from the region around the GC. Their spatial distribution of 6.4 keV line in the GC is shown in figure 1 where spikes of this emission correspond to directions to molecular clouds.

![Figure 1](image-url)

**Fig. 1.** Longitude (along $b = -0^\circ 046$) and latitude ($l = -0^\circ 17$) distributions of the 6.4 keV line in the GC as observed by Suzaku. The data-points taken from Uchiyama et al. (2011)

We expect that characteristics of the 6.4 keV emission produced by subrelativistic cosmic-rays and by a flux of primary X-ray photons are quite different. Below we reproduce spatial distributions of the 6.4 keV line in the framework of XRN and LECRp models.

### 3. Spatial Distribution of the Diffuse 6.4 keV Line Emission in the XRN Model

It is assumed in the XRN model that Sgr A* was active for about $T_1$ years in the past as an emitter of primary X-ray photons with the energy $E_x$. The average luminosity of this source during the active period is

$$L_{fl} \approx 10^{39} \text{ erg s}^{-1}$$

(5)

for the range 2–10 keV. The source activity is supposed to cease $T$ years ago.

For the observed spectrum (2) we define the total density of primary photons on the divergent front of primary photons, which is at the distance $r$ from Sgr A*, as

$$n_{ph} = \frac{L_{fl}}{4\pi cr^2 E_{x}^{min} \ln(E_{x}^{max}/E_{x}^{min})}$$

(6)

where $E_{x}^{min}$ and $E_{x}^{max}$ are the minimum and maximum energies of the spectrum of primary photons. Then the differential spectrum of primary photons $dn(E_x)/dE_x$ for the total photon density (6) we present as

$$\frac{dn(E_x)}{dE_x} = n_{ph} F_x(E_x)$$

(7)

with the normalization condition for $F_x(E_x)$
\[
\int_{E_x^{\min}}^{E_x^{\max}} F_x(E_x) dE_x = 1
\]

Therefore for the spectrum (2) we have

\[
F_x(E_x) = \frac{E_x^{\min} E_x^{\max}}{(E_x^{\max} - E_x^{\min})} E_x^{-2} \theta(E_x - E_x^{\min}) \theta(E_x^{\max} - E_x) \approx \frac{E_x^{\min} E_x^{\max}}{(E_x^{\max} - E_x^{\min})} E_x^{-2} \theta(E_x - E_x^{\min}) \theta(E_x^{\max} - E_x), \quad \text{for } E_x^{\max} \gg E_x^{\min}
\]

Here \( \theta(y) \) is the Heaviside step function.

These primary photons ionize iron atoms. The cross-section of photoionization \( \sigma_K \) has a form

\[
\sigma_K(E_x) = \sigma_0 \left( \frac{E_x}{E_0} \right)^{-3} \theta(E_x - E_0)
\]

where \( E_0 = 7.1 \ \text{keV} \) and \( \sigma_0 \sim 3 \times 10^{-20} \ \text{cm}^2 \) (see Tatischeff 2003).

Then the emissivity of the 6.4 keV line is

\[
\epsilon_{6.4}(r) = c \eta \omega_K n_H n_{ph} \int_{E_0}^{E_x^{\max}} \sigma_x(E_x) F_x(E_x) dE_x = \frac{E_x^{\min}}{4E_0} \left( 1 - \frac{E_0^4}{E_x^{\max}^4} \right) \approx \eta \omega_K \sigma_0 n_H \frac{L_H}{4\pi r^2 \ln(E_x^{\max}/E_x^{\min})} \frac{1}{4E_0},
\]

where \( \omega_K \) is the fluorescence yield of X-ray photon emission, which is about 0.3 for iron. The average density of the diffuse molecular gas was defined as \( n_H \). Below we take everywhere for calculations \( n_H = 10 \ \text{cm}^{-3} \) and assume a uniform density distribution of the molecular gas in the GC that gives an upper limit of diffuse 6.4 keV emission from the GC. The iron abundance \( \eta \) is supposed to equal twice solar, \( \eta = 2 \eta_\odot \approx 7 \times 10^{-5} \).

For the delay time \( T \) we can observe at present an irradiate emission of the diffuse gas which is on surface of the parabola (see e.g. Sunyaev & Churazov 1998)

\[
\frac{z}{c} = \frac{1}{2T} \left[ T^2 - \left( \frac{x}{c} \right)^2 \right],
\]

where the coordinates \( x \) and \( z \) are shown in figure 2.

Unlike the line emission from compact molecular clouds which can be observed for a relatively short period of time when the X-ray front is crossing a cloud (\( \sim 10 \) years), the diffuse 6.4 keV emission produced by primary X-ray photons should be permanently observed from the GC as the front of primary X-ray photons is propagating though the diffuse molecular gas in the GC.

The region emitting the 6.4 keV line by the diffuse gas - X-ray photon interactions is enclosed between the two surfaces determined by the time \( \tau_1 = T \) and \( \tau_2 = T + T_1 \) (see Eq. (12)) whose thickness is \( \Delta z \) between \( z_1 \) corresponding \( t = \tau_1 \) and \( z_2 \) corresponding \( t = \tau_2 \). We showed the geometry of the emitting region in figure 2.

The radial distance from Sgr A* is \( r^2 = x^2 + z^2 \). For the galactic plane (galactic latitude \( b = 0^\circ \)) the coordinate \( x \approx R_\odot \vartheta \) for small values of the galactic latitudes \( l = \vartheta \) where \( R_\odot = 8.5 \ \text{kpc} \) is the
Fig. 2. Geometry of the GC reflection process. The source Sgr A* in the coordinate center. Two parabolas shown by solid lines denote the reflection positions of emission emitted in the time interval $\{\tau_1, \tau_2\}$ which can be observed by an observer at present. Two circles (thin lines) denote a schematic position of the front of primary X-ray photons emitted by Sgr A* for the period $T_1$ which stopped its activity $T$ years ago. The dashed line is the line of view of the observer. Two thin arrow lines show the path of a primary photon before and after reflection.

distance between the GC and Earth.

Then the intensity of the diffuse 6.4 keV emission in the latitude direction $\vartheta$ is

$$I_{6.4}(x,t) = \frac{1}{4\pi} \int_{z_1}^{z_2} \epsilon_{6.4}(r,t)dz = \eta\omega_K\sigma_0n_H \left(\frac{L_{fl}}{(4\pi)^2\ln(E_{x,max}^{max}/E_{x,min})}\right) \frac{1}{4E_0} \int_{z_1}^{z_2} \frac{dz}{x^2 + z^2},$$

(13)

If the central source was active for the period between time momenta $\tau_2$ and $\tau_1$, then the limits of integration are

$$z_1 = \frac{1}{2} \left[ c\tau_1 - \frac{x^2}{c\tau_1} \right]$$

(14)

and

$$z_2 = \frac{1}{2} \left[ c\tau_2 - \frac{x^2}{c\tau_2} \right]$$

(15)

Below we define $E_{x,min} = 2$ keV and $E_{x,max} = 10$ keV that correspond to the value of $L_{fl}$ which was derived for this energy range, then
\[ I_{6.4}(x,t) = \frac{4.62 \times 10^{13} \text{ ph s}^{-1} \text{ cm}^{-1} \text{ sq.min}^{-1}}{x} \times \left( \frac{\eta}{2\eta_\odot} \right) \left( \frac{n_H}{10 \text{ cm}^{-3}} \right) \left( \frac{L_{fl}}{10^{39} \text{ erg s}^{-1}} \right) \times \left[ \arctan \left( \frac{1}{2} \left( \frac{cT_2}{x} - \frac{x}{cT_2} \right) \right) - \arctan \left( \frac{1}{2} \left( \frac{cT_1}{x} - \frac{x}{cT_1} \right) \right) \right]. \] \hspace{1cm} (16)

As an example we show in figure 3 the spatial and time variations of 6.4 keV line intensity in the direction of the Galactic latitude \( \vartheta \) \((x = R_\odot \vartheta)\) calculated from (16) when a central source starts its activity at \( t = 0 \) and this activity drops to zero at \( t = 300 \) yr.

From this figure one can see that unlike emission from molecular clouds, which can be observed for short periods of their irradiation \((\sim 10 \text{ years})\), the diffuse emission of 6.4 keV line from the GC can be permanently seen for \( \sim 10^2 - 10^3 \) year even when a period of X-ray protons injection by Sgr A* is quite short.

Ponti et al. (2010) estimated the following parameters of the primary flare: \( T = 100 \) yr and \( T_1 = 300 \) yr. The expected distribution of the diffuse X-ray emission in the XRN model is shown in figure 4 by the solid line. To reproduce the observed intensity distribution of the diffuse 6.4 keV line in the GC, the power of the central source of primary photons should be

\[ L_{fl} = 1.6 \times 10^{39} \times \left( \frac{n_H}{10 \text{ cm}^{-3}} \right)^{-1} \left( \frac{\eta}{2\eta_\odot} \right)^{-1} \text{ erg s}^{-1} \] \hspace{1cm} (17)

that is compatible with \( L_{fl} \) derived for the case of Sgr B2 by Murakami et al. (2000).

We notice, however, that the X-ray flare duration from Sgr A* may be much shorter that estimated by Ponti et al. (2010). Thus, from 6.4 keV flux variations in the direction of Sgr B2 presented
in Inui et al. (2009) the total duration of the flare may be about $T_1 \sim 10$ years only (see also in this respect Yu et al. 2011). In figure 4 the emission distribution for this duration of the flare is shown by the dashed line. The required luminosity of the flare in this case should be about $L_{fl} \sim 2.9 \times 10^{40}$ erg s$^{-1}$ that is still compatible with the estimate of Murakami et al. (2000) because the real distance from Sgr A* to Sgr B2 may be longer than the projection distance of 100 pc. If, however, the flare of Sgr A* occurred 300 yr ago, then the required luminosity is $L_{fl} \sim 7.8 \times 10^{40}$ erg s$^{-1}$.

As it was shown in Nobukawa et al. (2010) and Dogiel et al. (2011) the equivalent width of the iron line provided information about the line origin since the continuum and line X-ray emission were generated by the same primary particles (photons or subrelativistic charged particles). The continuum emission in XRN model is caused by Thomson scattering of primary photons and it should correlate with the 6.4 keV line emission. The continuum emission due to the Compton echo from molecular clouds was analysed in details by Sunyaev & Churazov (1998). The intensity of photons due to the Compton scattering of primary photons on the diffuse molecular gas can be estimated as

$$
(dI/dE)_c(x) = n_H n_{ph} \int_{z_1}^{z_2} F_x \sigma_T(\phi)dz = 0.5n_H r_e^2 \frac{L_{fl}}{4\pi E_x^2 \ln(E_x^{max}/E_x^{min})} \int_{z_1}^{z_2} \left( \frac{1 + \cos^2 \phi}{x^2 + z^2} \right) dz,
$$

(18)

here $\sigma_T$ is the Thomson cross-section, $r_e$ is the classical radius of electron and $\phi$ is the scattering angle. Taking into account that $\cos \phi = z/r$ we obtain that

$$
(dI/dE)_c(x) = \frac{n_H r_e^2 L_{fl}}{8\pi E_x^2 \ln(E_x^{max}/E_x^{min})} \left[ \frac{3}{x} (\arctan \frac{z_2}{x} - \arctan \frac{z_1}{x}) + \frac{z_2}{x^2 + z_1^2} - \frac{z_1}{x^2 + z_2^2} \right].
$$

(19)

The distribution of the equivalent width along the Galactic longitude expected in the framework of XRN model is shown in figure 5. Spatial variations of $eW$ for the XRN model are due to the cross-section dependence on the angle scattering. We notice, however, it is not easy to compare this
distribution of $eW$ with that derived from observations because it is not easy to subtract a component of diffuse X-ray emission produced by the Compton scattering from the total flux of X-ray in the direction of GC: a significant contribution of thermal emission is expected from there. Therefore, a special procedure to subtract a Compton component of continuum emission is necessary, as it was done e.g. in Koyama et al. (2009).

4. Spatial Distribution of the 6.4 keV Line in the LECRp Model

Another mechanism which can generate a diffuse component of 6.4 keV emission in the GC is bombardment of the interstellar molecular gas by subrelativistic protons whose lifetime is long enough to fill an extended region around the GC. As follows from Dogiel et al. (2009a); Dogiel et al. (2011) these protons may be generated by accretion processes onto the central black hole. The time-dependent spectrum of subrelativistic protons, $N(r, E, t)$ can be calculated from the equation (see for details Dogiel et al. 2009b; Dogiel et al. 2009d)

$$
\frac{\partial N}{\partial t} - \nabla D \nabla N + \frac{\partial}{\partial E} (b(E)N) = Q(E, r, t),
$$

(20)

where $D$ is the spatial diffusion coefficient of cosmic-ray protons, $dE/dt \equiv b(E)$ is the rate of proton energy losses, and $Q(E, t)$ is the rate of proton production by accretion, which can be presented in the form

$$
Q(E, r, t) = \sum_{k=0}^{\infty} Q_k(E) \delta(t - t_k) \delta(r),
$$

(21)

where $t_k$ is the injection time. The average time of star capture in the Galaxy was taken to be $T \simeq 10^4$
years, then \( t_k = k \times T \), where \( k \) is the number of a capture event.

The energy distribution of erupted nuclei \( Q_k(E) \) is taken as a simple Gaussian

\[
Q_k(E) = \frac{N_k}{\sigma \sqrt{2\pi}} \exp\left[-\frac{(E - E_{esc})^2}{2\sigma^2}\right],
\]

where we take the width \( \sigma = 0.03E_{esc} \) with \( E_{esc} \simeq 100 \) MeV, and \( N_k \) is total amount of particles ejected by each event of stellar capture.

In the nonrelativistic case the rate of energy losses of protons due to Coulomb collisions can be approximated as (see e.g. Hayakawa 1969)

\[
\left(\frac{dE}{dt}\right)_i \simeq \frac{4\pi n_{He} e^4 \ln \Lambda}{m_e v} \simeq \frac{a}{\sqrt{E}},
\]

where \( \ln \Lambda \) is the Coulomb logarithm, \( v \) is the proton velocity, \( m_e \) is the electron rest mass and \( a \) is a constant if we neglect a weak dependence of the Coulomb logarithm on the particle kinetic energy \( E \). Then the solution of Eq. (20) is

\[
N(r,E,t) = \sum_{k=0} \frac{N_k \sqrt{E}}{\sigma \sqrt{2\pi} Y_{1/3}} \exp\left[-\frac{(E_{esc} - Y_{2/3})^2}{2\sigma^2} - \frac{r^2}{4\pi D(t-t_k)}\right],
\]

where

\[
Y_k(t,E) = \left[\frac{3a}{2}(t-t_k) + E^{3/2}\right].
\]

and \( N_k \) is the total number of subrelativistic protons emitted in each star capture event, and \( T \) is the average time of star capture.

The intensity \( I \) of 6.4 keV line emission in any direction \( s \) produced by subrelativistic protons is calculated in the same way as in Dogiel et al. (2009b)

\[
I_{6.4}(s) = \omega_K \eta n_H \int ds \int_E N(E,r) v \sigma_K dE
\]

where the integration is along the line of sight \( s \). Here the cross-section \( \sigma_K \) for subrelativistic protons was taken from Tatischeff (2003).

The result of calculation for the LECRp model for the average gas density \( n_H = 10 \) cm\(^{-3}\) is shown in figure 6 for different values of the diffusion coefficient in the GC. For calculations we used the following extreme parameters of the proton injection: each star capture ejects \( N_k = 6 \times 10^{56} \) subrelativistic protons, the capture frequency is \( T_c = 10^4 \) yr (see Dogiel et al. 2009d). From the figure 6 one can see that the LECRp model can also reproduce the observed diffuse 6.4 keV emission in the GC for this set of the parameters.

In figure 7 we show expected time variations of the 6.4 keV line emission in the XRN model and the quasi-stationary component of 6.4 keV emission produced by subrelativistic protons. For the both cases the gas density was taken as \( n_H = 10 \) cm\(^{-3}\). From the figure we see that the 6.4 keV emission produced by protons may exceed that of primary XRN photons from Sgr A* in 100 years.
Fig. 6. Expected distribution of the diffuse 6.4 keV line along the longitude as observed from Earth calculated in the framework of the LECRp model for different values of the diffusion coefficient in the GC ($T_c = 10^4$ yr, $N_k = 6 \times 10^{56}$ pr).

from now if the parameters of these models were chosen correctly. In this case it is highly improbable to observe the stationary component of this line produced by the protons from the diffuse molecular gas in the foreseeable future.

However, we notice that if parameters of the XRN model like the energy flux of primary photons from Sgr A*, $L_{fl} \sim 3 - 10 \times 10^{39}$ erg s$^{-1}$ and the delay time $T \sim 100 - 300$ yr and the flare duration $T_1 \sim 10 - 300$ yr for Sgr B2 are more or less correctly estimated that makes derived values of 6.4 keV emission from the GC generated by primary photons relatively reliable, parameters of the LECRp model are highly uncertain. We do not know exactly which sort of stars and when was captured by the central black hole, how many protons escape into the GC medium, what is the diffusion coefficient there etc.

The continuum emission in LECRp model is caused by the inverse bremsstrahlung process (see Hayakawa 1969). Its intensity is

$$
(dI/dE)_c(s) = \omega_K \eta \eta H \int \frac{ds}{s} \int E N(E,r) v \frac{d\sigma_{IB}}{dE} dE
$$

(27)

where

$$
\frac{d\sigma_{IB}}{dE} = \frac{8}{3} Z^2 e^2 \left( \frac{e}{\sqrt{2} \sqrt{mc^2}} \right)^2 \frac{mc^2}{E'} \frac{1}{E_x} \ln \left( \frac{\sqrt{E'} + \sqrt{E' - E_x}}{E_x} \right)^2
$$

(28)

is the cross-section of the inverse bremsstrahlung process, $E$ is the energy of proton, $E' = \frac{m}{M} E$, $m$ is the mass of the electron and $M$ is the mass of the proton. The corresponding equivalent width in frame of LECRp model is shown in figure 5 by the dashed line.
The diffuse emission of the 6.4 keV line in the GC region was recently observed with Suzaku. Only two components can generate ionization of the molecular gas in this extended region, namely, hard X-ray photons or subrelativistic protons with energies about 100 MeV. Because of their long lifetime hard X-ray photons and subrelativistic protons can propagate over large distances.

Temporal characteristics of the diffuse line emission differ from that of compact clouds. Emission produced by photoionization in the clouds shows temporal variations with the characteristic time about several years that corresponds to the time in which a photon crosses the cloud. On the other hand, the diffuse emission generated by photionization changes with the characteristic time about \( \lesssim 10^{3} \) yr. Protons in both cases generate a stationary flux of the line emission.

We conclude that the diffuse emission of 6.4 keV line observed at present is probably due to 6.4 keV vacancy production by primary photons. This model describes nicely the observed intensity and spatial distribution of the 6.4 keV line emission around the GC. We notice, however, that the luminosity of Sgr A* required to produce the intensity of the observed diffuse emission depends strongly on the duration of Sgr A* X-ray flare. For the delay time \( T \sim 100 \) yr and the flare duration \( T_1 \) from 10 to 300 yr this luminosity is about \( L_X \sim 10^{39} - 10^{40} \) erg s\(^{-1}\) that is compatible with the value derived by Murakami et al. (2000) from the observed 6.4 keV flux from the cloud Sgr B2. If however the duration is about \( T_1 \sim 10 \) yr and the delay time \( T \sim 300 \) yr, then the required luminosity should be as high as \( \sim 10^{41} \) erg s\(^{-1}\) that exceeds significantly the estimate of Murakami et al. (2000) derived from the Sgr B2 data.

In principle these emission can also be described in the framework of LECRp model when the...
continuum and line emission is generated by protons but in this case extreme parameters of the LECRp model are necessary. The main problem of LECRp model is that we don’t know reliable estimates of protons injection by accretion processes, the proton spectrum, characteristics of proton propagation in the central region (diffusion coefficient) etc. With all these uncertainties we can conclude that at present the XRN model seems to be more attractive for interpretation of the diffuse line emission in the GC than the LECRp model though we cannot exclude that protons may contribute a significant part of the diffuse flux.

We hope that more reliable conclusions can be obtained in the near future. The first key results would be if observations find a stationary component of 6.4 keV line emission from molecular clouds. In this case the density of subrelativistic photons and a flux of diffuse line emission generated by protons can be estimated for the GC region.

Another very important parameter of the emission can be obtained with the planned Astro-H mission. The point is that the width of the 6.4 keV line produced by protons is about several tens of eV, which is about one order of magnitude wider than the width expected from that generated by X-ray reflection. Future observations by Astro-H SXS, whose energy resolution is supposed to be only 7 eV (see Takahashi et al. 2010) will be able to measure this parameter.

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