Line and Continuum Emission from the Galactic Center.

III. Origin of 6.4 keV Line Emission from Molecular Clouds in the Galactic Center

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Abstract

We analyze the 6.4 keV line and continuum emission from the molecular cloud Sgr B2 and the source HESS J1745-303, which is supposed to be a complex of molecular gas. From the HESS results it follows that Sgr A$^*$ is a source of high energy protons, which penetrate into molecular clouds producing there a TeV gamma-ray flux. We present arguments that Sgr A$^*$ may also produce a flux of subrelativistic protons which generate the 6.4 keV line and bremsstrahlung continuum emission from the clouds.

Key words: Galaxy: center - X-rays: diffuse background - ISM: molecular clouds: cosmic rays

1. Introduction

In the two previous papers of this series (Dogiel 2009ab) we presented arguments in favor of the injection of subrelativistic protons by star accretion on the central black hole. We showed that this process might explain the origin of hot plasma in the Galactic center and could produce a flux de-excitation gamma-ray lines and non-thermal X-ray emission observed by Suzaku in the range 14 to 40 keV (Yuasa et al. 2008). Below we analyze the origin of the 6.4
keV emission from molecular clouds in the Galactic center (GC) which may also be generated by these subrelativistic protons.

One of the first observations of X-ray emission from molecular clouds was performed by Sunyaev et al. (1993) who found a flux of X-rays from compact sources in the GC. They assumed that a large portion of this flux arises from Thomson scattering (reflection) by dense molecular clouds which are irradiated by a nearby X-ray source, e.g., by a flux from the central supermassive black hole, which was active in the recent past (∼300 – 400 years ago) but is almost unseen at present. They predicted also a bright fluorescent Kα line in the scattered spectrum of the clouds due to the K-absorption of photons with energies $E > 7.1$ keV. This line was discovered then with the ASCA telescope from the molecular cloud Sgr B2 (Koyama et al. 1996; Murakami et al. 2000) and from Sgr C (Murakami et al. 2001a). Later on 6.4 keV emission was discovered also in other molecular clouds (Bamba et al. 2002; Predehl et al. 2003; Nobukawa et al. 2008; Nakajima et al. 2009; Koyama et al. 2009). In subsequent publications based on observations with Chandra (Murakami et al. 2001b) and Suzaku (Koyama et al. 2007a; Nakajima et al. 2009) arguments were presented that the Sgr B2 and Sgr C clouds are, indeed, X-ray reflection nebula (XRN) irradiated by Sgr A∗ which was X-ray bright 300 years ago. Murakami et al. (2003) analyzing intensities of 6.4 keV line emissions measured by Chandra from the giant molecular clouds in the GC region: Sgr B2, Sgr C, and M0.11-0.08, obtained the luminosity history of the Galactic nuclei Sgr A∗ during the last 500 years. They concluded that Sgr A∗ was as luminous as $10^{39}$ erg s⁻¹ a few hundreds years ago, and has dimmed gradually since then.

Sunyaev & Churazov (1998) provided theoretical treatments of continuum and line emission from molecular clouds exposed by external sources. They showed that a short time variability was the key to investigate the nature of radiating sources from the shape and time variations of the 6.4 keV line. Since the light crossing time of Sgr B2 is about 30 years, they predicted a decline of the 6.4 keV line flux by a factor of 2 for the period of 10 years.

Using archival data of ASCA, BeppoSAX, Chandra, and XMM observatories Revnivtsev et al. (2004) found no significant variability of the line flux from Sgr B2 during the period 1993 - 2001. The constancy of the line flux meant that the luminosity of Sgr A∗ remained approximately constant for more than 10 years a few hundred years ago, while the fact that other molecular clouds in the GC region also shined in the 6.4 keV line indicated that the entire period of activity lasted much longer than 10 years.

Very recently Koyama et al. (2008a) and Inui et al. (2009) presented new Suzaku data which, in combination with ASCA, XMM-Newton and Chandra data, showed a time-variability of the 6.4 keV line emission from Sgr B2. It was concluded from a cross-correlation between the X-ray telescopes which measured this flux during different periods of time that this line exhibited a brightest peak in 2000 but fell down to 60% of the peak in 2005.

Since in the framework of XRN model the 6.4 keV line emission and the reflected con-
tinuum fluxes from molecular clouds are generated by the same primary X-ray radiation from an external source one expects a time-correlation between these fluxes. However, INTEGRAL observations indicate that the continuum 18 – 60 keV flux was constant within 25% during 2003 – 2004 (Revnivtsev et al. 2004). However, 6 year monitoring of the Sgr B2 region by INTEGRAL Terrier et al. (2009) gave evidence that a continuum flux from there in the range 20-40 keV was also time-variable with a decrease of more than 30%.

Recently Bamba et al. (2009) found 6.4 keV emission in the direction of the source of TeV gamma-rays (HESS J1745-303). This source is supposed to be a complex of molecular gas. Aharonian et al. (2008) showed that the TeV gamma-ray emission is most probably produced by a flux of high energy protons. From the spectral analysis it was concluded that this complex might also be an XRN source irradiated by Sgr A* or the nearby SNR G359.1-05.

If this molecular cloud is filled with high energy charged protons, as follows from the HESS data, then the question is whether these particles can also generate emission of the iron line from this cloud. We have reasons to assume that Sgr A* produces high energy protons not only in the TeV energy range but also in the GeV (see Cheng et al. 2007) and the MeV (see Dogiel et al. 2009a) ranges. If so, then the XRN interpretation cannot be considered as unique and others are also possible, especially as some results of observations of the 6.4 keV line emission from clouds do not fall into the XRN model, that cannot be completely ignored.

Thus, Predehl et al. (2003) presented their measurements of the 6.4 keV line from the GC made with XMM-Newton. They measured this emission from several molecular complexes situated at distances of 30 pc to 115 pc from Sgr A* and found that their surface brightness did not differ very much despite of their different distances from Sgr A*, though one could expect that more distant filaments should be dimmer at least by a factor of ten if they are XRNs. A key characteristic of the XRN model is a pronounced K-absorption edge at 7.1 keV in clouds. However, the XMM-Newton measurements are completely consistent with interstellar absorption only and do not show a significant absorption from clouds.

An alternative interpretation of the origin of the Kα fluorescent line in the Galaxy is its excitation by subrelativistic charged particles, i.e. electrons or protons (see Dogiel et al. 1998; Valinia et al. 2000; Yusef-Zadeh et al. 2002; Yusef-Zadeh et al. 2007a; Yusef-Zadeh et al. 2007b). Below we define this model as sources of X-rays emitted by charged particles (XECP).

We derive characteristics of the line and continuum emission from the clouds Sgr B2 and the source HESS J1745-303 assuming that this emission is generated by a flux of protons produced by Sgr A* from star accretion onto the central black hole.

2. Medium Parameters

The medium parameters near the GC are quite uncertain. Even the total mass of the most massive cloud Sgr B is poorly known. The estimated mass in the 42 pc diameter ranges from $2 \cdot 10^5$ to $7 \cdot 10^6 M_\odot$ (Oka et al. 1998). The cloud optical depth to Thomson scattering of
X-ray photons \( \tau \sim \sigma_T n_{H_2} r \), where \( n_{H_2} \) is the number density of gas and \( r \) is the cloud radius, is estimated to have the value \( \tau \simeq 0.4 \) (Revnivtsev et al. 2004).

The total mass of the complex HESS J1745-303 is estimated by the value \( 5 \cdot 10^4 \, M_\odot \) (Aharonian et al. 2008). In Table 1 taken from Bamba et al. (2009) we present the total gas mass, the angular and linear sizes of region emitting the 6.4 keV line and the projection distances from Sgr A* for these two clouds. The angular distances give only projection values,

|                         | Sgr B2       | J1745-303 |
|-------------------------|--------------|-----------|
| \( \text{M} [M_\odot] \) | 6 \cdot 10^6 | 5 \cdot 10^4 |
| Angular size [deg.]     | 0.05         | 0.3       |
| Linear size [pc]        | 7            | 40        |
| Distance [deg.]         | 0.7          | 1.2       |
| Linear distance [pc]    | \sim 100     | \sim 200  |

therefore, we estimate linear distances from Sgr A* to the clouds in the framework of XECP model.

The iron abundance is also poorly known. Direct estimations of this value provided by the Suzaku group (Koyama et al. 2007b; Koyama et al. 2009) gave the iron abundance in the intercloud medium at the GC from 1 to 3.5 solar. Revnivtsev et al. (2004) got the iron abundance for the cloud Sgr B2 at about 1.9 solar.

The average plasma density of the intercloud medium in the GC ranges between \( n \simeq 0.1 \) - 0.4 cm\(^{-3}\). The plasma temperature is around \( T \simeq 6.5 \) keV (see Koyama et al. 1996; Muno et al. 2004; Koyama et al. 2007b).

With all these uncertainties of parameters it is difficult to get reliable quantitative estimates. We can conclude only whether the XECP model can in principle reproduce these set of observational data or not. More reliable quantitative conclusions can be derived from future experiments.

3. Flux Parameters

Since molecular clouds are extended sources of 6.4 keV and continuum emission and their boundaries are not clear, their fluxes estimated from observation depend on the size of the source and background regions from which the spectrum is extracted. This circumstance complicates significantly estimations of emission fluxes from molecular clouds.

From observations the following parameters of the continuum in the range 2(4)-10 keV
range and 6.4 keV line emission were obtained for Sgr B2 and HESS J1745-303 (Koyama et al. 1996; Murakami et al. 2000; Murakami et al. 2001b; Koyama et al. 2007a; Aharonian et al. 2008; Bamba et al. 2009; Inui et al. 2009).

They are presented in Tables 2 and 3. We make absorption corrections of the Suzaku upper limit (Bamba et al. 2009) and the XMM-Newton upper limit (Aharonian et al. 2008) of the continuum emission from HESS J1745-303 for the average gas column density $L_{\text{av}} H \simeq 1.3 \cdot 10^{22}$ cm$^{-2}$ and for the extreme value of $L_{\text{ex}} H \simeq 4.6 \cdot 10^{23}$ cm$^{-2}$ which follows from the Aharonian et al. (2008) estimation of the cloud gas density equaling $5 \cdot 10^3$ cm$^{-3}$. These values are shown in Table 3, without and with brackets respectively.

Table 2. 6.4 keV Line flux as observed from Earth ($F_{6.4}$) and the continuum emission in the range 2(4)-10 keV ($\Phi_{2(4)-10}$ keV) from Sgr B2$^a$.

| Telescope   | $10^5 \cdot F_{6.4}$ | $10^{-33} \cdot \Phi_{2(4)-10}$ keV |
|-------------|----------------------|-------------------------------------|
|             | (ph cm$^{-2}$s$^{-1}$)| (erg s$^{-1}$)                       |
| ASCA        | 16.3                 | 110 – 140                           |
| Chandra     | 13.7-17.1            | 80 – 120                            |
| Suzaku      | 11.4                 | 97                                  |

$^a$ Absorption corrected luminosity. The intensities of 6.4 keV line were taken from Tables 2 and 3 of Inui et al. (2009).

Table 3. Flux of 6.4 keV line as observed from Earth, ($F_{6.4}$), and upper limits of the continuum emission in the range 2-10 keV ($\Phi_{2-10}$ keV) from HESS J1745-303$^a$.

| Telescope   | $10^5 \cdot F_{6.4}$ | $10^{-33} \cdot \Phi_{2-10}$ keV |
|-------------|----------------------|----------------------------------|
|             | (ph cm$^{-2}$s$^{-1}$)| (erg s$^{-1}$)                   |
| Suzaku      | 1.1                  | < 3.9 ( < 80)                    |
|             |                      | 90% confidence limit             |
| XMM-Newton  | -                    | < 9.6 ( < 226)                   |
|             |                      | 99% confidence limit             |

$^a$ Absorption corrected luminosity.

Below we analyze whether this emission can be generated by subrelativistic protons.

4. Spectrum of Subrelativistic Protons in the GC Region

In order to calculate a flux of X-ray emission from clouds produced by protons we should estimate their density nearby these clouds and inside them. The average diffusion coefficient of cosmic rays in the Galactic disk equals $D \simeq 10^{27}$ cm$^2$s$^{-1}$ (Berezinskii et al. 1990). Each event of star accretion on the central black hole produces about $Q = 10^{57}$ subrelativistic protons with
an energy of about $E_m \sim 100$ MeV (Dogiel et al. 2009a). The characteristic time of one solar mass star capture is $\tau_k \simeq 10^4$ years (Syer & Ulmer 1999). The injection function for a single star capture event can be presented as a simple Gaussian distribution

$$Q_k(E) = \frac{N}{\sigma \sqrt{2\pi}} \exp \left[ -\frac{(E - E_m)^2}{2\sigma^2} \right],$$

(1)

where we take the width $\sigma = 0.03E_m$ with $E_m = 100$ MeV, and $Q$ is total amount of particles ejected by one stellar capture event. The index $k$ denotes the number of capture events. Then time of the $k$th capture is $t_k = k \times \tau_k$.

The distribution of MeV protons in the GC region can be calculated from the three-dimensional diffusion equation:

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

(2)

where the rate of ionization losses is

$$\left( \frac{dE}{dt} \right)_i \equiv b(E) = -\frac{2\pi n e^4}{mv} \ln \Lambda.$$  

(3)

Here $m$ is the electron mass, $v$ is the proton velocity and $\ln \Lambda$ is the Coulomb logarithm. The source term has the form

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

(4)

where $t_k$ is the injection time, and the functions $Q_k(E)$ are given by Eq. (1). The solution of Eq. (2) is presented in Dogiel et al. (2009a).

$$N(r, E, t) = \sum_{k=0} \frac{Q_k \sqrt{E}}{\sigma \sqrt{2\pi} Y_{1/3} k} \theta(t - t_k) \times$$

$$\exp \left[ -\frac{(E_{esc} - Y_{2/3}^2)^2}{2\sigma^2} - \frac{r^2}{4D(t-t_k)} \right] \frac{r^2}{(4\pi D(t-t_k))^{3/2}},$$

(5)

where $\theta(t - t_k)$ is the Heaviside (step) function, and

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

(6)

In Table 4 we summarize the parameters of proton production and propagation in the intercloud medium of the GC, which we use for calculations.

5. Proton density inside molecular clouds

We denote by $N_c(E)$ the proton spectrum on the surface of clouds which is calculated from Eq. (5). The proton distribution inside the cloud depends on the processes of proton penetration into dense neutral gas. This mechanism is also uncertain but as it was shown in
Table 4. Parameters of proton production and propagation in the hot GC plasma

| Part.inj. numb. | Star capt. time | Part.inj. energy | Plasma dens. | Plasma temp. | Diff. coeff. |
|----------------|-----------------|------------------|--------------|--------------|--------------|
| $N_p$          | $\tau_k$        | $E_m$            | $n$          | $T$          | $D$          |
| $10^{57}$ prot.| $10^4$ year     | $100$ MeV        | $0.2$ cm$^{-3}$ | $6.5$ keV     | $10^{27}$ cm$^2$s$^{-1}$ |

Dogiel et al. (1987) that strong fluctuations of the magnetic field induced by the observed gas turbulence inside molecular clouds made particle propagation there similar to diffusion with the coefficient $D_c$ ranging from $10^{24}$ to $10^{26}$ cm$^2$s$^{-1}$ depending on cloud parameters. In the framework of the one-dimensional diffusion approximation we calculate the proton distribution inside molecular clouds.

In order to calculate the distribution of protons inside molecular clouds we should derive their spectrum at cloud surfaces. The linear distances from Sgr $A^*$ to the clouds was derived in order to reproduce the line $F_{6.4}$ and continuum $\Phi_x$ emission from the clouds. These distances was estimated as $\sim 100$ pc for Sgr B2 and $\sim 450$ pc for HESS J1745-303.

Spectra of subrelativistic protons $N_p(E)$ calculated from Eq. (5) for the clouds Sgr B2 (solid line) and HESS J1745-303 (dashed-dotted line) are shown in Fig. 1.

![Figure 1](image)

**Fig. 1.** Spectra of protons injected by Sgr $A^*$ near the clouds Sgr B2 (solid line) and HESS J1745-303 (dashed-dotted line). The distance from Sgr $A^*$ to the cloud Sgr B2 is 100 pc and to HESS J1745-303 - 450 pc. These values were chosen in order to reproduce the observational data from Table 2-3.

The gas distribution in the cloud Sgr B2 is highly nonuniform. It has an envelope that extends to $\sim 45$ pc with the average density $\sim 10^3$ cm$^{-3}$ and a dense core of 5-10 pc with the density about $\sim 10^6$ cm$^{-3}$. Its density distribution can be described as (see Lis & Goldsmith
\[ \left( \frac{n_{H_2}}{1 \text{ cm}^{-3}} \right) = 5.5 \times 10^4 \left( \frac{r}{1.25 \text{ pc}} \right)^2 + 2.2 \times 10^3. \] (7)

For calculations we take the average value of the gas density there to be \( \bar{n}_{H_2} = 10^4 \text{ cm}^{-3} \). Almost the same gas density for HESS J1745-303 was estimated by Aharonian et al (2008).

The iron abundance inside these clouds were taken to be 2 solar, though similar calculations can be performed for other set of parameters. Spatial parameters of clouds, which we used for calculations, are shown in Table 5.

**Table 5.** Molecular cloud parameters (denoted by "c")

| Gas dens. | Gas temp. | Fe Abund. | Diff. coeff. |
|-----------|-----------|-----------|--------------|
| \( \bar{n}_c \) | \( T_c \) | \( \eta_c \) | \( D_c \) |
| \( 10^4 \text{ cm}^{-3} \) | 100 eV | \( 7.4 \times 10^{-5} \) | \( 10^{25} \text{ cm}^2\text{s}^{-1} \) |

The spectrum of protons, \( \tilde{N}_p(E, x) \), penetrating into the molecular clouds can be calculated in the framework of one-dimensional diffusion equations for the derived spectrum \( N_c(E) \) on cloud surfaces. Here \( x \) is the coordinate from the cloud surface to the cloud center.

\[
\frac{\partial}{\partial E} \left( b_c(E) \tilde{N} \right) - D_c \frac{\partial^2}{\partial x^2} \tilde{N} = 0,
\] (8)

with the boundary conditions

\[
\tilde{N}|_{x=0} = N_c, \quad \tilde{N}_p|_{x=\infty} = 0. \tag{9}
\]

The solution of the equation can be obtained by the method of images (Morse & Feshbach 1953):

\[
\tilde{N}(E, x) = \frac{x}{|b_c(E)|} \int_E^{E_m} \frac{dE_0 N_c(E_0)}{\sqrt{D_c \cdot \tau_c(E, E_0)^{3/2}}} \times
\]

\[
\times \exp \left[ -\frac{x^2}{4D_c \cdot \tau_c(E, E_0)} \right]. \tag{10}
\]

Here \( b_c(E) \) is the rate of ionization losses inside the cloud and

\[
\tau_c(E, E_0) = \int_{E_0}^{E} \frac{dt}{b_c(t)}. \tag{11}
\]

As follows from Eq. (10), subrelativistic protons are unable to fill the whole volume of the cloud. They penetrate into the clouds from outside for a depth \( \sim \sqrt{\tau_c(E)D_c} \), which is about 0.1 – 0.3 pc.
6. Continuum and 6.4 keV fluxes from molecular clouds

In order to calculate the flux of 6.4 keV line from the clouds we used the proton distribution in the cloud (10) and the cross-section of Kα vacancy production, σK, by protons from Garcia et al. (1973).

Then the flux of 6.4 keV line is calculated from

\[
F_{6.4} = \frac{R^2 \eta \omega_K \bar{n}_c}{d^2} \int_0^\infty dx \int_E^{\infty} v(E) \sigma_K \bar{N}(E, x) dE ,
\]

(12)

where \( \omega_K \) is the fluorescence yield of X-ray photon emission, which is about 0.3 for iron, and \( \eta \) is the iron abundance, \( R \) is the radius of the region emitting the 6.4 keV line (see Table 1).

The Doppler line width generated by proton impact is broader than that produced by e.g., electron impact (see Dogiel et al. 1998). For the width of the iron line observed by the Suzaku the velocity of the iron atoms cannot be higher than 150 km s\(^{-1}\) (Koyama et al. 2007b). The average velocity of iron atoms after collision with a subrelativistic proton is smaller than 100 km s\(^{-1}\). Therefore, for protons with energies \( E < 100 \) MeV the width line is about \( \lesssim 30 \) eV that is inside the Suzaku Gaussian of the 6.4 keV line width \( \sim 120 \) eV (Ebisawa et al. 2008).

Protons penetrating into molecular clouds generate also X-ray continuum by inverse bremsstrahlung. The cross-section of inverse bremsstrahlung is (Hayakawa 1969)

\[
\frac{d\sigma_{br}}{dE_x} = \frac{8}{3} Z^2 e^2 \left( \frac{e^2}{mc^2} \right)^2 \frac{m c^2}{E'} \frac{1}{E_x} \ln \left( \frac{\sqrt{E'} + \sqrt{E' - E_x}}{E_x} \right)^2 .
\]

(13)

Here \( E' = (m/M) E_p \). Then the flux of inverse bremsstrahlung radiation can be calculated from

\[
\Phi_x = 4\pi R^2 \int_0^\infty N_p(E, r, t) \frac{d\sigma_{br}}{dE_x} v_p \bar{n} dx .
\]

(14)

The results of the flux calculations are summarized in Table 6.

| Cloud     | \(10^5 \cdot F_{6.4}\) | \(10^{-33} \cdot \Phi_{2-10 \text{ keV}}\) |
|-----------|------------------------|---------------------------------|
| SGR B2    | 11                     | 80                             |
| J1745-303 | 1.1                    | 7.6                            |

From a comparison of the calculation results with the data for the clouds Sgr B2 and HESS J1745-303 (see Tables 2, 3 and 6) we see their coincidence. This means that the XECP model of X-ray production by protons inside molecular clouds is reasonable.

The spectrum of bremsstrahlung photons from the cloud Sgr B2 as observed from Earth is shown in Fig. 2.
We notice that the $K\alpha$ vacancies and bremsstrahlung emission can also be produced by primary electrons generated by accretion processes and by knock-on electrons generated directly inside clouds by collisions of primary protons with the gas. However estimates show that the energy of primary electrons is about 50 keV for the used accretion parameters. Therefore, their lifetime is relatively short because of ionization losses. The contribution of secondary electrons to the total X-ray flux is about three times smaller than that of primary protons (Dogiel et al. 1998).

Our analysis shows that there should a component of nonthermal continuum X-ray emission whose intensity is proportional to the intensity of the 6.4 keV line, and as follows from Dogiel et al. (2009b) the intensity of the 6.7 keV line and nonthermal continuum from the plasma should also correlate with each other. This conclusion naturally explains the results presented by Koyama et al. (2009) who found two components of nonthermal emission from the GC whose intensities are proportional to the fluxes of the 6.7 and 6.4 keV lines, respectively. Both components have the same spectral index, that is not surprising in the framework of XEPC model because emission of these components from the hot plasma and the cold gas in the GC is generated by the same flux of protons.

Since the total mass of molecular gas in the inner Galaxy can be as high as $7 \cdot 10^7 M_\odot$, i.e about one order of magnitude larger than the mass of Sgr B2, then molecular clouds may contribute a significant part of the total hard X-ray flux from the GC.

7. Heating and ionization of molecular gas in the GC by subrelativistic protons

Ionization and heating of molecular clouds in the Galactic disk is an old problem (for reviews on this subject (see Dalgarno & McCray 1972, and Spitzer & Jenkins 1975). We still do not know the unobserved energetic radiation which maintains the heating and ionization state
of the interstellar gas. Hypothetical sources which in principle could deposit significant power into the interstellar gas were considered to be either soft X-rays (Silk & Werner 1969) or a flux of cosmic rays (Hayakawa et al. 1961; Spitzer 1968) in the form of protons with energies $2 - 10$ MeV (see e.g. Nath & Biermann 1994 and Indriolo et al. 2009) or in the form of subrelativistic electrons (see e.g. Sacher & Schönfelder 1984 and Dogiel et al. 2002).

Parameters of the molecular gas in the GC are even more specific. As Yusef-Zadeh et al. (2007b) noticed the molecular gas in GC is heated up to a temperature higher than in the disk, $T_c \sim 100 - 200$ K. Therefore, a global heating mechanism is needed there to explain the high gas temperature.

Yusef-Zadeh et al. (2002); Yusef-Zadeh et al. (2007a) assumed that the processes of 6.4 keV line emission and the gas ionization and heating are produced by low-energy cosmic ray electrons with energies below 1 MeV which are completely absorbed by molecular clouds. The inferred ionization rates $\zeta$ of the GC clouds based on the 6.4 keV line measurements range between $2 \cdot 10^{-14}$ s$^{-1}$H$^{-1}$ and $5 \cdot 10^{-13}$ s$^{-1}$H$^{-1}$. Calculations of Neufeld et al. (1995) showed that the ionization rate $\zeta$ of the order of $10^{-13}$ s$^{-1}$H$^{-1}$ is high enough in order to heat the molecular gas in the GC up to 200 K.

In the framework of the XECP model the density of subrelativistic protons in the GC is almost uniform within 50 pc that explains: a) an almost uniform temperature distribution there (see, e.g., Nobukawa et al. 2008); and b) a constant surface brightness of the molecular clouds in the GC, which does not differ very much despite of their different distances of molecular clouds from Sgr A$^*$ (Predehl et al. 2003). If the 6.4 keV flux is provided by protons, then in the central region we expect, indeed, a constant emissivity of 6.4 keV line in clouds independently of the distance from Sgr A$^*$.

We estimate the ionization rate $\zeta$ per one atom of H, which can be provided by subrelativistic protons in Sgr B2 from the relation

$$\zeta \simeq \int \sigma_i v \frac{dN}{dE} dE \ (\text{sec}^{-1}\text{H}^{-1}).$$

(15)

where the ionization cross-section $\sigma_i$ was taken from e.g. Spitzer & Tomasko (1968).

As calculations show the rate of ionization in clouds is strongly nonuniform. It is very high at a cloud surface, $\zeta \gtrsim 10^{-13}$ s$^{-1}$H$^{-1}$, but decreases almost to zero at distances $\sim 0.1 - 0.3$ pc from the surfaces.

8. Conclusion

We showed in the paper that:

- From the HESS observations it follows that Sgr A$^*$ may be a source of high energy protons which penetrate into molecular clouds. If the injection spectrum of the protons continues into the MeV range, then these protons generate continuous and line X-ray emission from
For the derived injection rate of protons with energies $\lesssim 100$ MeV the observed line and continuum emission from hot plasma and molecular gas in the GC is generated by the same protons;

Our model naturally explains the origin of the two components of nonthermal emission observed by Suzaku, which are proportional to the 6.4 and 6.7 keV line fluxes, respectively;

The observed time-variations of the 6.4 keV flux from molecular clouds are strongly in favor of the XRN model, but they do not exclude simultaneous production of the 6.4 keV line by other processes, e.g., like this one, especially as some observational results cannot be interpreted in the framework of the XRN model;

It follows from our estimations that molecular clouds may contribute a significant part of the total hard X-ray flux from the GC.

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 natural width expected from that generated by subrelativistic electrons or X-ray reflection. Future observations by Astro-H SXS, whose energy resolution is supposed to be only 7 eV (Takahashi et al. 2008) will be able to measure this parameter and, thus, to resolve the origin of the K$\alpha$ line emission from the GC;

Unlike other astrophysical problems, that of the 6.4 keV flux can be solved in the near future because of its fast time-variability. The 6.4 keV flux from Sgr B2 had dropped for the period from 2000 to 2005 to 60% of its maximum value. If Sgr B2 is an XRN source then one expects that this cloud will be almost unseen in several years. If so, then no explanation is acceptable except the X-ray reflection. Otherwise, the origin of the emission from Sgr B2 should be explained by other processes including this one;

We showed that the density of subrelativistic protons is almost constant in the GC, which explains the constant plasma temperature in this region, $T \sim 6.5$ keV, as observed by Suzaku and a constant surface brightness of molecular clouds in the GC as observed by SMM-Newton, which cannot be interpreted in the framework of the XRN model.

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