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X- and Gamma-Ray Emission from the Galactic Center

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Abstract. We discuss the origin of continuum and line X-ray emission observed in the direction the Galactic Center. We predict a significant flux of de-excitation gamma-ray lines in this direction, which can be produced by sub-relativistic protons generated by accretion processes.

1. Introduction

Galactic center (GC) is a harbour of high energy activity which is observed in different ranges of electromagnetic waves.

The inner 10 pc of our Galaxy is a source of the very high energy \(\gamma\)-rays \((E_\gamma > 100\text{ GeV})\) coincident with the position of the supermassive black hole Sgr A* (Acero et al. 2009).

The EGRET telescope (see Mayer-Hasselwander et al. 1998) found a gamma-ray flux toward the Galactic Center of the order of \(2 \cdot 10^{37}\) erg s\(^{-1}\) for energies \(E>500\text{ MeV}\) in an error circle of 0.2 degree radius.

The INTEGRAL team measured a 511 keV line of width 2.2 keV, with a flux \(1.01 \cdot 10^{-3}\) photons cm\(^{-2}\) s\(^{-1}\). The bulge annihilation emission is highly symmetric with an extension of 5-8 degree. (see e.g., Churazov et al. 2005).

Last Suzaku observations of Koyama et al. (2007) found a clear evidence for a hot plasma in the GC with the diameter about 20 arcminutes (i.e. \(\sim 50 - 60\) pc). The total X-ray flux from this region in the range 2 to 10 keV is \(F_X \sim 2 \cdot 10^{36}\) erg s\(^{-1}\), and the total energy of plasma in this region is about \(3 \cdot 10^{52}\) erg. Such a high plasma temperature is surprising, since it could not be gravitationally confined and a very high amount of energy \((\sim 10^{42}\text{ erg s}^{-1})\) is required to maintain the plasma outflow (see, e.g. Koyama et al. 1996). This energy supply cannot be produced by SN explosions and other more powerful sources of energy are required to support the energy balance there.

Intensive emission in X-ray iron lines is observed from the Galactic center, which is often explained that the gas there was exposed in the past by sources of intensive X-ray emission e.g., from a supernova or from the galactic nucleus (Sunyaev et al. 1993; Koyama et al. 1996).

The IBIS/ISGRI imager on the INTEGRAL observatory detected for the first time a hard continuum X-ray emission located within 1’ of Sgr A* over the energy range 20-100 keV (Belanger et al. 2006).
Latter [Koyama et al. (2007)] also found that the continuum flux from the GC contained an additional hard component. [Yuasa et al. (2008)] performed analysis of Suzaku data and showed a prominent hard X-ray emission in the range from 14 to 40 keV whose spectrum is a power law with the spectral index ranging from 1.8 to 2.5. The total luminosity of the power-law component from the central region is about $4 \times 10^{36}$ erg s$^{-1}$. The spatial distribution of hard X-rays correlates with the distribution of hot plasma.

We assume that this activity of the Galactic center in different ranges of waves has common origin, namely, it is due to processes of star accretion onto the central black hole.

In [Cheng et al. (2006, 2007)] we discussed the origin of the 511 keV annihilation flux from the GC region and production of continuum gamma-ray emission in the range $E_\gamma > 100$ MeV. The origin of the 511 keV line emission from the GC region is supposed to be due to annihilation of secondary positrons generated by $p - p$ collisions. Below we present a model of X-ray and de-excitation gamma-ray line emission which can also be produced by this activity.

2. Energy Release

Energy release of black holes due to processes of accretion can be observed in different wave ranges.

**X-rays.** The maximum flux of X-rays can be estimated from the equation for the Eddington emissivity,

$$L_{Edd} \simeq \frac{4\pi M_{bh} G m_p c}{\sigma_T} \quad (1)$$

For a black hole with the mass $M_{bh} \sim 10^6 M_\odot$ it give about $L_{Edd} \sim 10^{44}$ erg s$^{-1}$.

**Flux of relativistic charged particles.** Flux of relativistic particles in the form of jets (electrons or protons). The origin of relativistic protons in jets is still rather speculative but we have evidences in favour of their production near black holes (see Abraham et al. 2007; Istomin & Sol 2009). The energy carried away by relativistic protons is estimated as (see Cheng et al. 2006)

$$\Delta E_p \sim 5 \times 10^{51} (\eta_p/10^{-2}) (M_*/M_\odot) \text{erg}. \quad (2)$$

where $\eta_p$ is the conversion efficiency from accretion power into the the energy of jet motion and $M_*$ is the star mass.

**Flux of subrelativistic protons.** Once passing the pericenter, the star is tidally disrupted into a very long and dilute gas stream. The outcome of tidal disruption is that some energy is extracted out of the orbit to unbind the star and accelerate the debris. Initially about 50% of the stellar mass becomes tightly bound to the black hole , while the remainder 50% of the stellar mass is forcefully ejected (see, e.g. Ayal et al. 2000). The kinetic energy carried by the ejected debris is a function of the penetration parameter $b^{-1}$ and can significantly exceed that released by a normal supernova ($\sim 10^{51}$ erg) if the orbit is highly penetrating (see Alexander 2005),

$$W \sim 4 \times 10^{52} \left( \frac{M_*}{M_\odot} \right)^2 \left( \frac{R_*}{R_\odot} \right)^{-1} \left( \frac{M_{bh}/M_*}{10^6} \right)^{1/3} \left( \frac{b}{0.1} \right)^{-2} \text{erg}. \quad (3)$$
For the star capture time $\tau_s \sim 10^4$ years (see Alexander 2005) it gives a power input $W \sim < 3 \cdot 10^{42}$ erg s$^{-1}$. The mean kinetic energy per escaping nucleon is given by

$$E_{\text{esc}} \sim 42 \left( \frac{\eta}{0.5} \right)^{-1} \left( \frac{M_\ast}{M_\odot} \right) \left( \frac{R_\ast}{R_\odot} \right)^{-1} \left( \frac{M_{\text{bh}}/M_\ast}{10^6} \right)^{1/3} \left( \frac{b}{0.1} \right)^{-2} \text{MeV},$$  

where $\eta M_\ast$ is the mass of escaping material, $b$ is the ratio of $r_p - \text{the periapse distance (distance of closest approach)}$ to the tidal radius $R_T$. For the black-hole mass $M_{\text{bh}} = 4.31 \times 10^6 M_\odot$ the energy of escaping particles is $E_{\text{esc}} \sim 68(\eta/0.5)^{-1}(b/0.1)^{-2}$ MeV nucleon$^{-1}$ when a one-solar mass star is captured.

The dissipation times of these energy components released in accretion processes are quite different: if the duration time of X-ray emission $\tau_X$ from a black hole is about hundred years, the characteristic lifetime of relativistic protons can be (at some conditions) as small as $\tau_{rp} \sim 10^4$ years while that of 100 MeV subrelativistic protons is of the order of $\tau_{srp} \sim 10^7$ years (see Cheng et al. 2006; Dogiel et al. 2009b), i.e. $\tau_X, \tau_{rp} < \tau_s \ll \tau_{srp}$. In this respect processes concerned with subrelativistic protons can be considered as quasi-stationary (unlike that of X-rays or relativistic protons). Emission generated by subrelativistic protons is presented below.

3. Origin of X-ray Emission from the Galactic Center and Production of De-Excitation Gamma-Ray Lines There

**Thermal X-ray continuum.** The average power of energy release from accretion in the form of subrelativistic protons is about $10^{42}$ erg s$^{-1}$ and the average energy of these protons is about 100 MeV. These protons transform their energy into plasma heating by ionization losses. As derived by Sunyaev et al. (1993); Kovama et al. (1996) just this energy release is necessary to heat the plasma up to temperatures about $6 - 10$ keV, just as observed (see Dogiel et al. 2009).

**Non-thermal X-ray continuum.** The inverse bremsstrahlung losses of the protons produce a non-thermal X-ray flux in the range above 10 keV. For the parameters of accretion the inverse bremsstrahlung flux of protons is about $3 \times 10^{36}$ erg s$^{-1}$, (see Dogiel et al. 2009) i.e. about the flux observed by Suzaku from the GC in the 14 – 40 keV band (Yuasa et al. 2008).

**Flux of 6.4 keV iron line from molecular clouds.** As we mentioned above the GC is active not only in X-ray continuum but high fluxes of 6.4 keV iron line are observed in the direction of molecular clouds in the GC. One of the interpretations is that these flux arise due to the K-absorption of photons with energies $E > 7.1$ keV by dense molecular clouds irradiated by a nearby X-ray source, which was active in the recent past ($\sim 300 - 400$ years ago) but is almost unseen at present (Sunyaev et al. 1993; Kovama et al 1996). In this case the 6.4 keV emission from the Galactic center is observed by chance and its duration cannot be longer than several ten years.

An alternative interpretation of the origin of the K fluorescent line in the Galaxy is its excitation by subrelativistic charged particles, i.e., by electrons (see e.g. Yusef-Zadeh et al. 2002) or protons (see Dogiel et al. 1998).

The proton distribution inside the cloud depends on the processes of proton penetration into dense neutral gas. As it was shown in Dogiel et al. (1987)
strong fluctuations of the magnetic field are induced by the observed gas turbulence inside molecular clouds that makes cosmic ray propagation there similar to diffusion with a relatively small diffusion coefficient. Therefore, subrelativistic protons are able to fill a part of the cloud volume, i.e. a surface envelope with the thickness $\lesssim 1$ pc. Our calculations show the rate of ionization in clouds by subrelativistic protons is strongly nonuniform. It is very high at the cloud surface, $\zeta \gtrsim 10^{-13}$ s$^{-1}$H$^{-1}$, but decreases almost to zero with the distances from the surfaces.

For the parameters of quasi-stationary flux of subrelativistic protons produced by accretion one can estimate a stationary flux of the iron line at Earth from, e.g. the cloud Sgr B2 which is at the level $\sim 10^{-4}$ ph cm$^{-2}$s$^{-1}$ (see Dogiel et al. [2009a]), i.e just as observed. In terms of the accretion model X-rays and subrelativistic protons are naturally produced by star capture processes. Then we expect time variable and stationary fluxes of 6.4 keV iron line emission from molecular clouds generated by X-ray photons and hundred MeV protons respectively.

*De-excitation gamma-ray lines.* Collisions of subrelativistic nuclei with ambient matter can lead to nuclear excitation and result in emission of de-excitation gamma-ray lines. These lines may be a good tracer for subrelativistic cosmic rays, because the line brightness can give us information about the amount of subrelativistic particles. Assuming that the mean metallicity in the GC region is two times higher than in the solar neighborhood, the total gamma-ray line flux below 8 MeV is $1.1 \times 10^{-4}$ photons cm$^{-2}$ s$^{-1}$. The most promising lines for detection are those at 4.44 and $\sim 6.2$ MeV, with a predicted flux in each line of $\approx 10^{-5}$ photons cm$^{-2}$ s$^{-1}$ (see Dogiel et al. [2009c]). These lines should be broad, $\Delta E_\gamma/E_\gamma$ of 3-4%, which unfortunately renders their detection with the INTEGRAL spectrometer unlikely but future gamma-ray missions may be able to test these predictions. Detection of the gamma-ray line emission produced by cosmic-ray interactions in the interstellar medium would provide insightful information on low-energy cosmic rays and give a significant advance in the development of the theory of cosmic-ray origin.

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