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Sagittarius A* Rivaled the Sun in the Ancient X-ray Sky

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ABSTRACT

Sagittarius A*, lying in the Galactic Center 8 kpc from Earth, hosts the closest supermassive black hole known to us. It is now inactive, but there are evidences indicating that about six million years ago it underwent a powerful outburst where the luminosity could have approached the Eddington limit. Motivated by the fact that in extragalaxies the supermassive black holes with similar masses and near-Eddington luminosities are usually strong X-ray emitters, we calculate here the X-ray luminosity of Sagittarius A*, assuming that the outburst was due to accretion of gas or tidal disruption of stars, both scenarios having been considered to trigger the previous outburst. We show that in both cases Sagittarius A* could precipitate on Earth an X-ray ($h\nu > 2$ keV) irradiance comparable to that from the current quiescent sun. The irradiance in harder energy band 20 keV $< h\nu <$ 100 keV, however, surpasses that from an X-class solar flare, and the irradiation timescale is also much longer, ranging from weeks to 10^5 years depending on the outburst scenario. This level of radiation would disturb the ozone and ionosphere around the ancient earth, and affect the abundance of organic molecules in dense interstellar environments around the solar neighbourhood, but these prospects have not been adequately explored so far. Our results indicate that the activity of supermassive black hole and the origin and evolution of life may be more closely linked than previously has been thought.

Subject headings: black hole physics – methods:analytical – Galaxy: center – X-rays: bursts

1. Introduction

Supermassive black holes (SMBHs), born in the early, more dynamic universe, intermittently underwent eruptions at the expense of the gravitational energies of the infalling gas or stars, but today they are mostly "dead", lurking in the nuclei of quiescent galaxies (Kormendy & Ho 2013). During the eruption, a SMBH becomes detectable in the electromagnetic window, and the phenomenon is called active galactic nucleus (AGN). The possibility that an AGN occurred a long time ago in our Galaxy [3] brought up some early

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[3]This possibility also inspired a science fiction, *The Inferno*, authored by Sir Fred Hoyle.

scientific discussions of its potential impact on terrestrial lives (Clarke 1981; Laviolette 1987; Gonzalez 2005).

Nevertheless, these prospects have not been actively pursued, partly because AGNs were thought to be uncommon –it was considered that AGNs are triggered by galaxy mergers, but there is evidence suggesting that our Galaxy has not experienced a substantial one during the past 10 billion years (Gilmore et al. 2002). There was also a practical difficulty. Although it had been realized that X-ray photons could penetrate the dusty Galactic plane and impact Earth (Gonzalez 2005), the X-ray radiation of an AGN had not been well characterized at that time, leaving large uncertainties in estimating the actual irradiance on Earth.

Recent studies, instead, suggest that Milky-Way-like galaxies frequently nurture AGNs (Hopkins & Hernquist 2006), about once every $10^7 - 10^8$ years per galaxy with each AGN lasting about 10^5 years. These statistics indicate that in the local universe the SMBHs less massive than $10^7\ M_\odot$ are activated not by galaxy mergers, but by stochastic processes such as gravitational instability. The stochastic mode explains the aforementioned outburst of Sagittarius A* (Sgr A* hereafter) which occurred merely $2-8$ million years ago (Nayakshin & Cuadra 2005; Su et al. 2010; Bland-Hawthorn et al. 2013; Ponti et al. 2013). The conjecture, that in this mode a low-mass black hole accretes matter at a high rate and grows rapidly (Hopkins & Hernquist 2006), also broadly agrees with the inferred luminosity of the Sgr A* outburst (Nayakshin & Cuadra 2005; Bland-Hawthorn et al. 2013), about $(3-100)\%$ of the Eddington limit $L_{\rm Edd} \simeq 5\times10^{44}$ erg s^{-1}.

AGNs radiating at near-Eddington rates are known to emit about 1% of their bolometric luminosity in hard X-ray ($h\nu > 2$ keV) (Jin et al. 2012; Vasudevan et al. 2014). This correlation is anticipated if there is a universal coronal structure covering the surface of accretion disk that powers an AGN (Lu & Yu 1999; Wang et al. 2004). If Sgr A* once was a normal AGN so that the X-ray luminosity reached $0.01L_{\rm Edd}$, then given its distance and the fact that hard X-ray photons suffer little attenuation in the Galactic plane, one will derive an irradiance of 10^{-3} erg s^{-1} cm^{-2} that will be incident on Earth. This is already comparable to the X-ray irradiance from the quiescent sun (Peres et al. 2000).

A sudden enhancement of the X-ray irradiation on Earth will immediately increase the ionization of the upper atmosphere, leading to a chain of secondary reactions, including ozone depletion and higher UV flux at the sea level (Dartnell 2011; Melott & Thomas 2011). The magnitudes of these changes are determined by the intensity and duration of the X-ray irradiation, as well as the spectral shape of the ionizing radiation. These factors, in the light of possible ancient outbursts from Sgr A* , will be quantified in this paper.

2. X-ray irradiation from Sagittarius A*

2.1. X-rays produced by an AGN

To assess the relative importance of the X-ray irradiation from Sgr A* , in Figure 1 we compare the irradiances on Earth from the sun (Peres et al. 2000) and from the active Sgr A* . For the latter, the intrinsic spectral energy distribution (SED, i.e. the luminosity per logarithmic energy bin) is computed using the templates compiled from a sample of unobscured AGNs (Jin et al. 2012). According to these templates, given the ratio $\lambda_{\rm Edd} \equiv L_{\rm bol}/L_{\rm Edd}$ between the bolometric luminosity $L_{\rm bol}$ and the Eddington luminosity $L_{\rm Edd}$, the luminosity $L_{2-10~\rm keV}$ of the photons in the band 2 keV $< h\nu <$ 10 keV scales as

$$\log(L_{2-10~\rm keV}/L_{\rm bol}) = -0.773\log(\lambda_{\rm Edd}) - 2.004. \quad (1)$$

The photon index Γ, the index of a power law which characterizes the number of photons in each energy bin, is given by

$$\Gamma = 0.564\log(\lambda_{\rm Edd}) + 2.246. \quad (2)$$

SED will have a power-law index of $-\Gamma+2$. When converting the SED to the spectral irradiance on Earth (νF_ν), the extinction law of the Galactic plane ($A_K = 7.0$ and $R_V = 3.1$) is applied (Tan & Draine 2004).

From Figure 1, we find that at $h\nu > 2$ keV the irradiance from the AGN, irrespective of the assumption of $\lambda_{\rm Edd}$, exceeds that of the sun during the solar minimum. Moreover, while the sun has a soft SED above $20-30$ keV ($\Gamma > 5$), the SED of the AGN is much harder, with a strong component in the high energy band, which normally extends to an energy band as high as $h\nu \sim 10^2$ keV (Vasudevan et al. 2014), the band of soft γ-ray. This component makes the AGN brighter than the sun in the hard-X-ray/soft-γ-ray sky, even when the sun is undergoing an X-class solar flare. For the AGN, we also see an increase of the irradiance at $h\nu > 10$ keV with decreasing $\lambda_{\rm Edd}$. This anti-correlation, which is a common feature for disk corona (Lu & Yu 1999; Wang et al. 2004), sustains the brightness of the AGN in the X-ray sky even when $L_{\rm bol}$ has dropped by a factor of 30.

2.2. X-rays from a tidal flare

The X-ray luminosity of Sgr A* can be temporarily enhanced also by tidal disruption of a nearby star (Rees 1988; Komossa 2012). The event rate is about once every $10^4 - 10^5$ years during the quiescent phase of Sgr A* (Merritt 2010), and during the AGN phase the rate can be even higher, because of the perturbation of the nearby stars by the accretion disk (Chen & Amaro-Seoane 2014). Except for those rare cases in which jets are produced and accidentally directed towards observers, a standard tidal flare has a soft, thermal SED with an effective temperature of $kT \simeq 0.1$ keV, therefore producing a negligible amount of hard X-ray. However, a small fraction of the tidal flares (Lin et al. 2011; Saxton et al. 2012; Nikołajuk & Walter 2013) do exhibit strong power-law components with $2 < \Gamma < 5$ in the energy band $h\nu > 2$ keV, which can not be attributed to jets (Komossa 2012), and instead, may be produced by shock-heated materials that are incompletely thermalized (Ulmer 1999; Strubbe & Quataert 2011).

Figure 2 compares the spectral irradiance of an AGN with that of a tidal flare, assuming a solar-type star being disrupted by Sgr A* . In our model the intrinsic SED of the tidal flare has two components, (1) a black-body emitter whose temperature and surface area are given by the standard model (Chen & Liu 2013), and (2) a power-law component with $\Gamma = 3$ whose luminosity is 10% of the black-body emission (Strubbe &

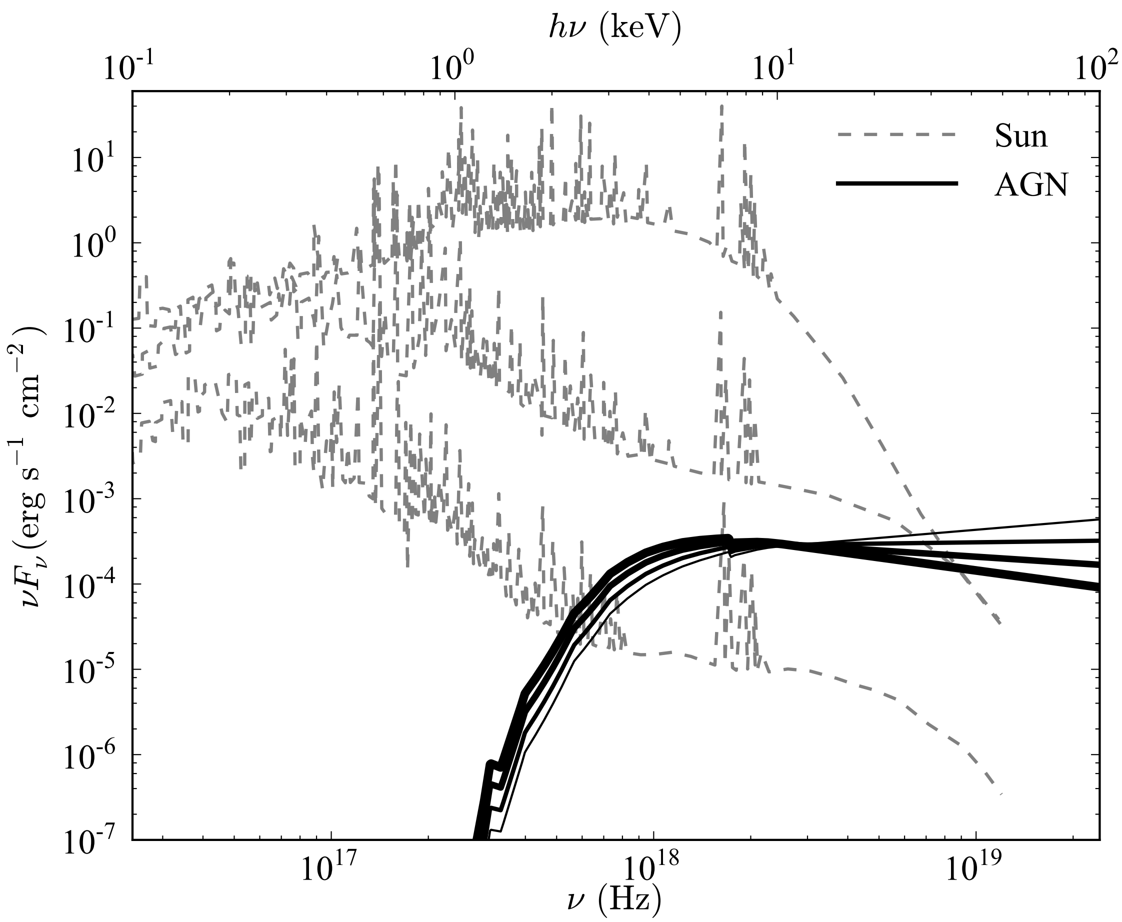

Fig. 1.— X-ray irradiances on Earth from different sources. The four solid lines show the irradiances from the AGN in the Galactic Center, and the increasing thickness corresponds to a increase of luminosity, i.e. $\lambda_{\rm Edd} = (0.1, 0.3, 1, 3)$. The three dashed curves are for the sun (Peres et al. 2000), and from top to bottom correspond to the irradiances of an X-class solar flare, the maximum state during the solar cycle, and the state during solar minimum.

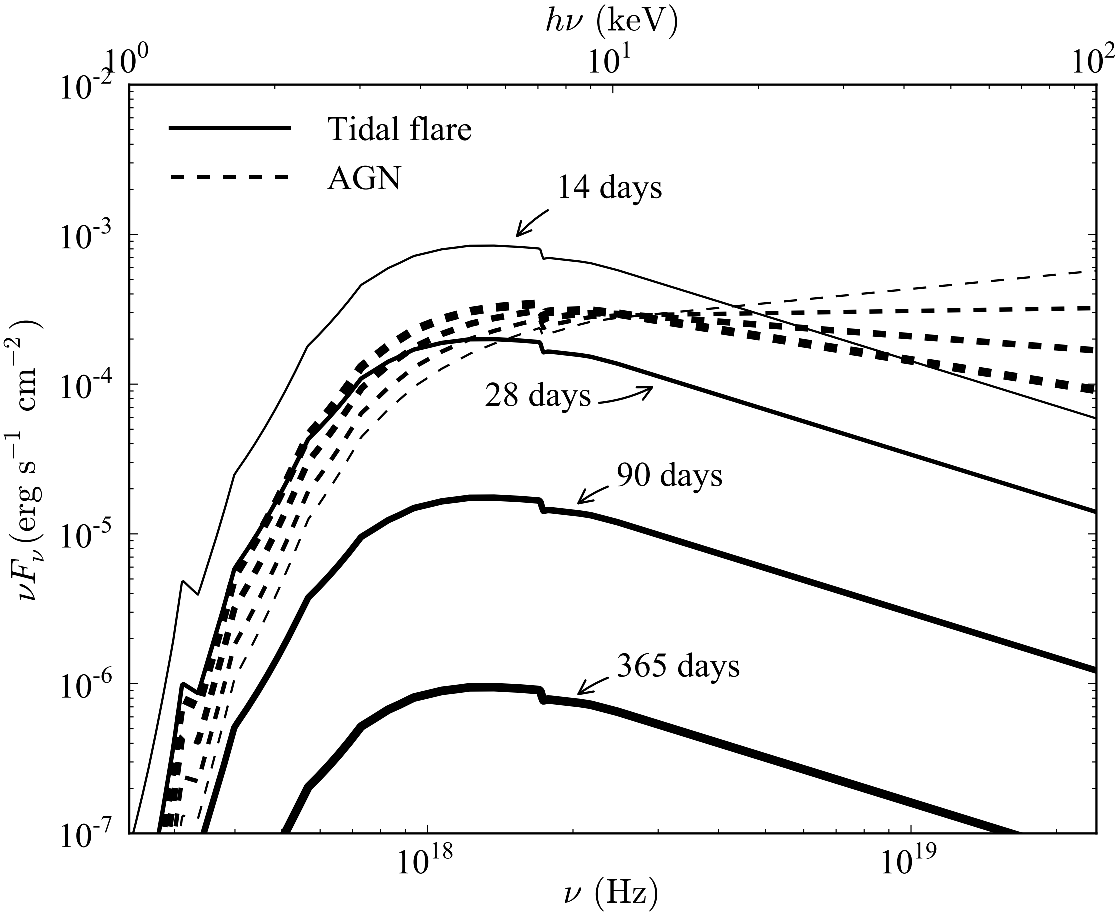

Fig. 2.— Comparing spectral irradiances from a tidal flare and an AGN. The four solid lines with increasing thickness depict the irradiances of the tidal flare $(14, 28, 90, 365)$ days after the initial outburst. The four dashed curves are for the AGN, adopted from Figure 1.

Quataert 2011). We do not know the SED in the first 14 days following the initial outburst, because during this period $L_{\rm bol} > 3L_{\rm Edd}$ according to our model, and an optical-thick wind may be present and obscuring the flare (Strubbe & Quataert 2011). Bearing in mind that assuming a different Γ or a different type of star also leads to some uncertainties in the SED, we conclude that a tidal flare during the first few weeks is as bright as an AGN.

3. Discussions

Although there is no calculation so far elaborating on the response of the Earth atmosphere to the above X-ray outbursts, earlier works on cataclysmic events with similar X-ray characteristics have provided some hints. For example, in the past 30 years several distant (soft) gamma-ray bursts (GRBs) had induced similar level of irradiation on Earth, about 10^{-3} erg s^{-1} cm^{-2} at $h\nu > 5$ keV, during which disturbances of the ionosphere had been detected (Fishman & Inan 1988; Inan et al. 1999; Mandea & Balasis 2006). The disturbance of the ionosphere by Sgr A* may be more serious, because tidal flares and AGNs last for a much longer time, ranging from a few weeks to as long as 10^5 years.

Besides irradiance, another quantity which is often used to evaluate the lethality of ionizing radiation is the so-called fluence, i.e. the total amount of radiation injected into one unit area on Earth. According to our models, the fluence ranges from 10^3 erg cm^{-2} during a one-week tidal flare to about 3×10^9 erg cm^{-2} during one AGN episode. For comparison, in a hypothetical scenario of a nearby supernova (Ruderman 1974; Ejzak et al. 2007), a dose of hard X-ray equivalent to $(10^6 - 10^8)$ erg cm^{-2} will be injected into the Earth's atmosphere, and the consequence is a depletion of the ozone by as much as 20%. Fortunately, the irradiation from Sgr A* , e.g. during an AGN, will be stretched over a period much longer than that of a supernova, leaving more time for the biosphere on Earth to adjust.

It is important to note that the irradiance from Sgr A* is constant across the solar system while that from the sun drops quickly with increasing distance. The consequence, as shown in Figure 3, is that from about 10 AU to the edge of the solar system, the irradiation from Sgr A* during its outburst predominates in the entire X-ray band of $h\nu > 1$ keV. Most of the gas giants in the solar system, including their moons, lie in this region, but the corresponding reaction of their atmosphere has not been explored.

Last but not least, X-ray irradiation can also drive the chemical reactions in dense molecular clouds (Krolik & Kallman 1983) and enhance the abundance of organic molecules in protoplanetary disks (Teske et al. 2011). The implication is that the ancient outbursts from Sgr A* may have played an important role in shaping the habitable environment in the solar system, as well as in other places throughout the Milky Way.

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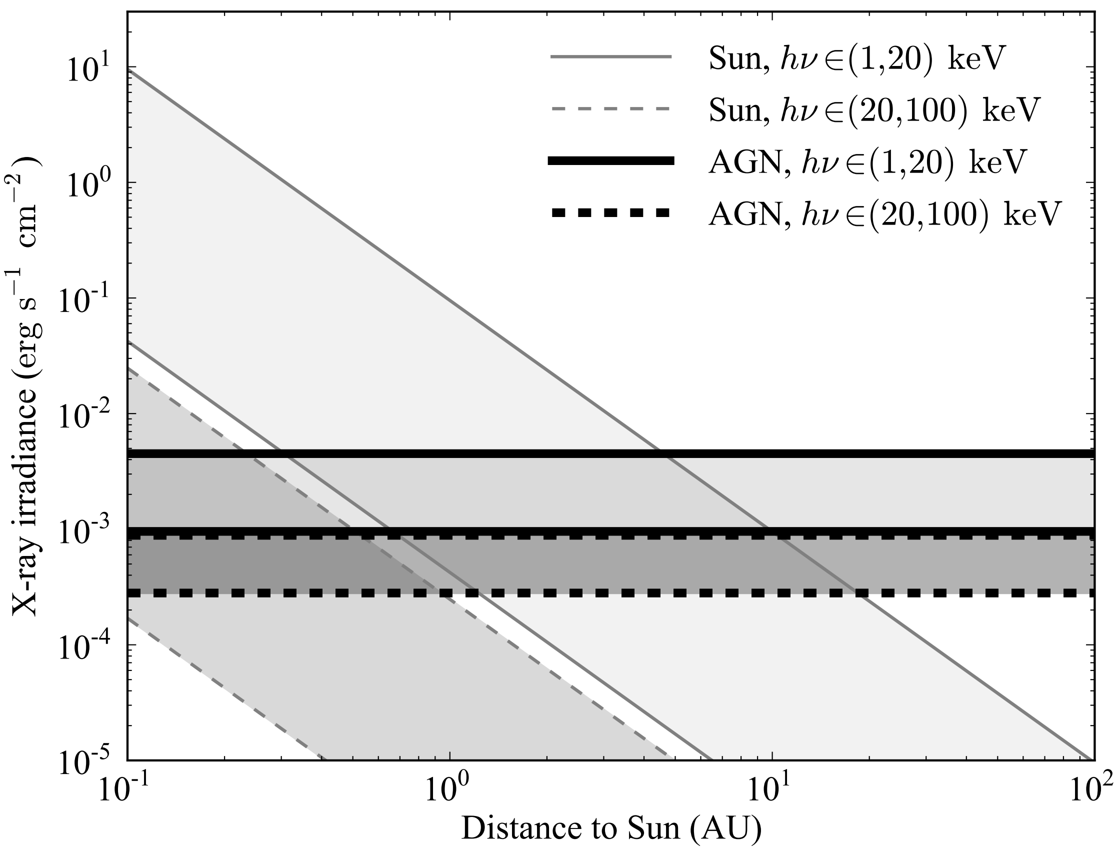

Fig. 3.— X-ray irradiances as a function of the distance to the sun. The solid lines (both grey and black) refer to the irradiances integrated over the energy band 1 keV $< h\nu <$ 20 keV, while the dashed ones correspond to the energy band 20 keV $< h\nu <$ 100 keV. The shaded areas bounded by the thin grey lines depict the variation of the irradiance from the sun during the solar cycle. The shaded areas deliminated by the thick black lines correspond to an AGN in the Galactic Center with $0.1 < \lambda_{\rm Edd} < 3$.

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