Low-Energy Cosmic Rays in the Galactic Center Region

V. TATISCHEFF[1], A. DECOURCHELLE[2], G. MAURIN[3]

[1] *Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, IN2P3/CNRS and Univ Paris-Sud, 91405 Orsay Campus, France*
[2] *Service d'Astrophysique (SAp)/IRFU/DSM/CEA Saclay, Bt 709, 91191 Gif-sur-Yvette Cedex, France; Laboratoire AIM, CEA-IRFU/CNRS/Univ Paris Diderot, CEA Saclay, 91191 Gif sur Yvette, France*
[3] *Laboratoire d'Annecy le Vieux de Physique des Particules, Univ de Savoie, CNRS, BP 110, 74941 Annecy-le-Vieux Cedex, France*

Vincent.Tatischeff@csnsm.in2p3.fr

Abstract: The Fe Kα line emission at 6.4 keV is often attributed to photoionized matter in the vicinity of a bright X-ray source. In the Galactic center region, the bulk of the 6.4 keV line emission is likely a fluorescence radiation testifying to a past X-ray flaring activity of the supermassive black hole at the center of the Milky Way. However, the Fe Kα line can also be excited by impacts of low-energy cosmic rays. Using data from *XMM-Newton*, we recently identified a large population of fast ions from the X-ray emission prominent in the 6.4 keV line emanating from the Arches cluster region. These low-energy cosmic rays are most likely accelerated in the bow shock created by the cluster's proper motion. However, such a cosmic-ray source is probably unique in the Galactic center environment.

Keywords: X-rays: ISM – cosmic rays – Galaxy: center – ISM: abundances.

1 Introduction

The detection of extended hard X-ray emission from the Galactic center (GC) region with the *Granat*/ART-P telescope prompted Sunyaev et al. [19] to predict the existence of a bright fluorescent radiation at 6.4 keV from hard X-ray photoionization of neutral to low-ionized Fe atoms in molecular gas clouds. Two bright regions in the 6.4 keV Fe Kα line were subsequently found with the *ASCA* satellite: one near the Sgr B2 cloud and the other near the Radio Arc [12]. The Fe Kα line emission from these regions was interpreted as resulting from the irradiation of dense molecular clouds by a powerful X-ray flare from the supermassive black hole Sgr A*. Recent observations of a temporal variation in the 6.4 keV line emission from various clouds of the Central Molecular Zone (CMZ) can indeed be explained by a sporadic increase of the X-ray flaring luminosity of Sgr A* in the past (see, e.g. [15, 3, 17]). In this model, the line flux variation results from the propagation of X-ray light fronts from outbursts of Sgr A* that occured in the last few hundred years.

The Fe Kα line at 6.4 keV can also be produced by collisional ionization of Fe atoms by impact of fast particles. Thus, at least part of the 6.4 keV emission from the central regions of the Galaxy could come from the bombardment of molecular gas by low-energy electrons [26, 27] or ions [7, 21]. In particular, Yusef-Zadeh et al. [27] recently suggested that the time variability of Fe Kα emission can be explained by the relatively short energy loss time of low-energy electrons diffusing in a dense molecular cloud.

Determining the relative contributions of these two models is essential, as they provide evidence for the past activity of the central black hole or for a large population of low-energy cosmic rays (LECR) in some regions of the GC. We first discuss some important properties of the LECR model in this context and then discuss more specifically the origin of the 6.4 keV line emission from the Arches cluster region.

2 Fe 6.4 keV line from the GC region: LECRs versus X-ray fluorescence

Three main observables can be used to distinguish whether a 6.4 keV line emission is produced by photoionization or collisional ionization induced by LECRs: (i) its time variability, (ii) its spectral properties, in particular the equivalent width (EW) of the Fe 6.4 keV line, and (iii) the absolute line intensity.

2.1 Time variability

The model puts forward in Ref. [27] for the variability of the 6.4 keV line emission is based on the short energy loss time of low-energy electrons in a dense molecular cloud. As shown in Fig. 1 (left panel), indeed $\tau_{\rm loss} < 1$ yr for electrons < 100 keV propagating in a medium of H density $n_{\rm H} = 10^4$ cm^{-3} ($\tau_{\rm loss}$ is inversely proportional to $n_{\rm H}$). Thus, an injection of LECR electrons in such a medium over a time interval that is very short compared to the lifetime against the ionization losses could induce a variation of the Fe line intensity on a yearly timescale, as observed in some GC regions. But the assumption of a brief period of injection is questionable, as the fast particles are expected *to diffuse* from their low-density acceleration region to denser molecular clouds. For a diffusion coefficient $D < 10^{27}$ cm^2 s^{-1}, as can be expected for LECRs in the GC environment (see, e.g., [1]), the diffusion time over a distance $d = 1$ pc is $\tau_{\rm diff} \sim d^2/D > 300$ yr, which is much longer than the X-ray variation time measured in various places.

Ponti et al. [15] observed a coherent time variability of 6.4 keV line emission from distant clouds that can be well explained as due to a superluminal motion of an X-ray light front illuminating a molecular cloud complex. A simultaneous variation of distant X-ray sources (see also [5]) cannot be explained satisfactorily by a model of LECRs.

Figure 1 also shows that LECR ions in the interstellar medium (ISM) cannot produce a short-term variation of the neutral Fe Kα line emission. Wee see in panel (b) that most of the emission at 6.4 keV is produced by protons

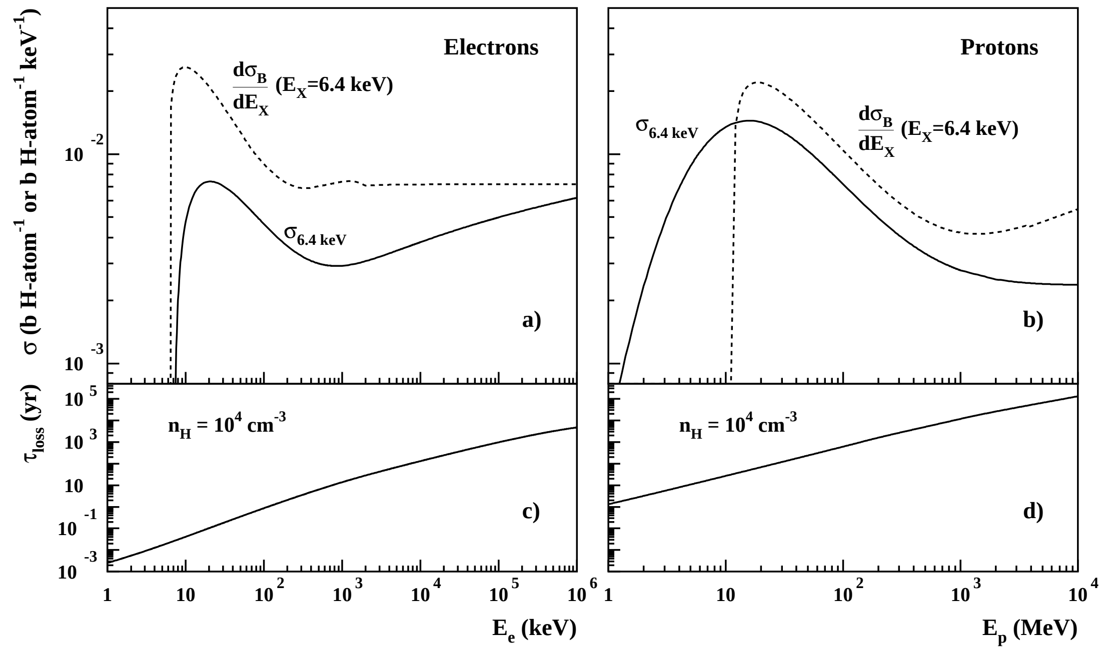

Figure 1: Panels **(a)** and **(b)**: cross sections involved in the calculation of the EW of the neutral Fe Kα line. *Solid lines*: cross sections (in units of barn per ambient H-atom) for producing the 6.4 keV line by the impact of fast electrons **(a)** and protons **(b)**, assuming solar metallicity. *Dashed lines*: differential cross section (in barn per H-atom per keV) for producing 6.4 keV X-rays by bremsstrahlung of fast electrons **(a)** and inverse bremsstrahlung from fast protons **(b)**, in a medium composed of H and He with H/He=0.1. The ratio of these two cross sections gives the EW of the 6.4 keV line (in keV) for a mono-energetic beam of accelerated particles. Panels **(c)** and **(d)**: energy loss time of fast electrons **(c)** and protons **(d)** propagating in a medium of H density $n_{\rm H} = 10^4$ cm^{-3}.

of kinetic energies $>$ 10 MeV, and the energy loss time of these particles in $n_{\rm H} = 10^4$ cm^{-3} is $>$ 30 yr (panel d).

2.2 Spectral properties: line EW and slope of the underlying continumm

As shown by Tatischeff et al. [21] (see also [27]), the EW of the 6.4 keV line produced by LECR electrons is largely independent of the energy distribution of the fast particles; it is typically $\lesssim$ 450 eV for interaction in a medium of solar metallicity. This can be understood from Fig. 1a, which shows that the cross section for producing the 6.4 keV line and the differential cross section for producing bremsstrahlung X-rays of the same energy have similar energy thresholds and shapes. The EW observed from the GC region is $>$ 1 keV in some places and sometimes equal to $\sim$ 2 keV (e.g. [16, 21]). To reproduce this value with the LECR electron model, the metallicity would thus need to be $\gtrsim$ 4.4 times solar in these regions, which is not supported by other abundance measurements (see, e.g., Ref. [24] and references therein).

We see in Fig. 1b that the cross section for the 6.4 keV line production by proton impact has a lower energy threshold than that for the bremsstrahlung continuum, which shows that LECR protons with a soft energy spectrum can produce a much higher EW of the 6.4 keV line than the electrons.

The slope of the X-ray continuum emission produced by LECRs can also differ between electrons and protons [21]. Indeed, it is likely that suprathermal electrons of energies $<$ 100 keV cannot freely penetrate into molecular clouds due to the existence of magnetic turbulence at cloud boundary [6]. As a result, the electron-produced continuum emission below 10 keV is predicted to be hard, with a photon index $\Gamma < 1.4$ (see Fig. 4 in [21]). Inverse bremsstrahlung of LECR ions can produce softer photon spectra, depending on the minimum kinetic energy of the particles succeeding in penetrating molecular clouds (see Fig. 9 in [21]).

K-shell vacancies created by electrons, protons and X-rays lead to line emission at the same energies. For heavy-ion collisions however, the lines could be shifted by several tens of electron-volts and significantly broadened [10]. In addition, very broad X-ray lines from de-excitations in fast heavy ions can be produced following charge exchange between accelerated particles and ambient atoms [20]. Thus, future high-resolution X-ray spectral observations of the Fe Kα line emission from the GC region could provide further constraints on the nature of the emission process and possibly on the composition of LECRs as well.

2.3 CR Energetics and ionization rate

The production of 6.4 keV line photons by both LECR electrons and ions is relatively inefficient, the radiation yield being typically on the order of 10^{-6} [21], meaning that a high power in LECRs should generally be needed to produce an observable neutral Fe Kα line by collisional ionization. Thus, a total kinetic power of $\sim 10^{41}$ erg in LECR electrons would be required to explain all the 6.4 keV line emission from the CMZ [27], which is comparable to the total power of Galactic CR ions (the power contained in GCR electrons is much less). There are no known sources able to sustain such an electron population throughout the CMZ.

The kinetic power contained in LECRs is essentially lost through ionization of molecular gas. Observations

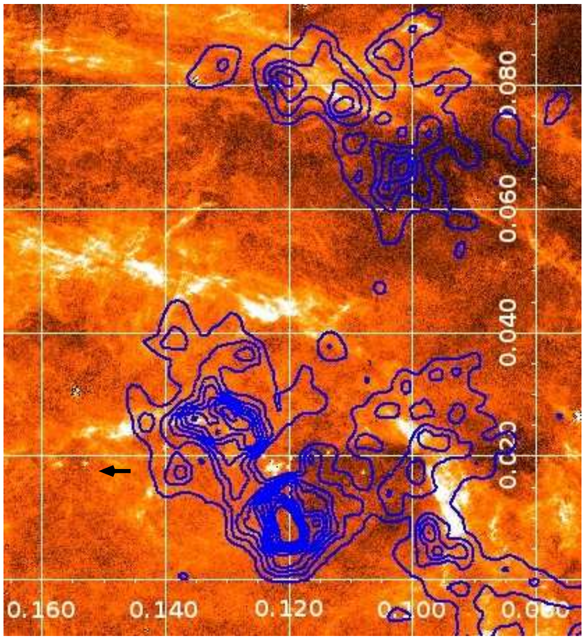

Figure 2: *XMM-Newton*/EPIC continuum-subtracted 6.4-keV line intensity contours (linearly spaced between 3×10^{-8} and 1.8×10^{-7} photons cm^{-2} s^{-1} arcmin^{-2}) overlaid with a *Hubble Space Telescope*/NICMOS map in the Paschen-α line [23, 9]. The axis of the map indicate galactic coordinates in degrees. The Arches cluster is located at $\ell \approx 0.122^\circ$ and $b \approx 0.018^\circ$. The black arrow illustrates the observed proper motion of the cluster, which is almost parallel to the Galactic plane [18, 4]. North is up and east is to the left.

of H_3^+ absorption lines generated by ionization of H_2 molecules show the existence throughout the CMZ of a pervasive, warm and diffuse molecular gas ionized at a rate of $\sim (1-3) \times 10^{-15}$ (see [11] and references therein). This gas is most likely ionized by LECRs, probably protons accelerated in SNRs, whose contribution into the diffuse 6.4 keV line emission recently detected by *Suzaku* [22] is negligible [8]. The latter radiation is most probably produced by the same hard X-ray outbursts from Sgr A* that also produce fluorescence 6.4 keV line emission in several dense molecular clouds.

3 The Fe 6.4 keV line emission from the Arches cluster region

Figure 2 shows a *XMM-Newton* map of the Arches cluster region in the 6.4 keV Fe Kα line [21], superimposed on a *Hubble*/NICMOS high-resolution map in the hydrogen Paschen-α (Pα) line [23, 9]. The Pα line emission is a sensitive tracer of massive stars – the Arches cluster is clearly visible in this figure at Galactic coordinates $(\ell, b) \approx (0.122^\circ, 0.018^\circ)$ – and of warm photoionized gas. The main diffuse Pα-emitting features in Fig. 2 are the Arched filaments, which are thought to be located at edges of molecular clouds photoionized by the adjacent star cluster [13]. Two bright 6.4 keV structures are visible in Fig. 2: one surrounding the star cluster and another further north from a region centered on $(\ell, b) \sim (0.11^\circ, 0.075^\circ)$. A fast variability of the Fe line emission was observed from the latter region, which suggests that it could result from the illumination of a molecular cloud by a nearby transient X-ray source [2].

In contrast, the 6.4 keV line flux from the region surrounding the Arches cluster was found to be consistent with being constant over ~ 8.5 years of *XMM-Newton* repeated observations [2, 21], which is probably a necessary condition for a cosmic-ray origin (Sect. 2.1). Capelli et al. [2] divided this area into two circular subregions of about 6 light-years diameter (at a distance of 8 kpc) and found that both subregions emit the Fe line at a constant flux. Other regions in the CMZ have been observed to emit a steady 6.4 keV line emission during about the same period, but they generally have larger spatial extents (see, e.g., [3]).

The morphology of the bright 6.4 keV structure surrounding the Arches cluster strongly suggests that the origin of this emission is related to the star cluster itself and not to a distant source such as Sgr A*. However, there is no X-ray source in the cluster capable of producing this emission by photoionization. The required 4 – 12 keV luminosity of such a source would need to be $\sim 5 \times 10^{35}$ erg s^{-1}, which is ~ 100 higher than the total, time-averaged, unabsorbed luminosity of the cluster [21]. We also note that such a bright source was not detected with the *Einstein* observatory in 1979 [25] and with subsequent X-ray observatories as well, which imposes a minimum distance of ~ 4.6 pc between the cloud emitting at 6.4 keV and the putative transient X-ray source. Furthermore, except for the X-ray binary GRS 1915+105, the outburst duration of transient X-ray sources is generally much shorter than 8.5 years. Finally, the Arches cluster is probably too young, $t \sim 2.5$ Myr [14], for an X-ray binary system to have formed within it.

For all of these reasons, the 6.4 keV line emission arising from the vicinity of the Arches cluster is unlikely to result from photoionization and is most probably produced by CR impact. We see in Fig. 2 that the X-ray structure seems to prolong the easternmost Arched filament E1, which partly traces a molecular cloud of the -30 km s^{-1} cloud complex that is probably interacting with the cluster (see [24] and references therein). The morphology of this structure shows two bright knots connected by a faint bridge to the east of the cluster, which is suggestive of a bow shock associated with a supersonic collision between the star cluster and the adjacent molecular cloud. The orientation of the bow-shock like structure is broadly consistent with the measured direction of motion of the cluster stars relative to the field population [18, 4].

In Tatischeff et al. [21], we developed detailed models for the production of line and continuum X-rays by interaction of accelerated electrons and ions with a neutral ambient gas. These models were then applied to *XMM-Newton* data of the X-ray emission surrounding the Arches cluster, and we found that this emission can be well-fitted with the combination of an optically thin thermal plasma and a nonthermal component produced by LECR ions. The best-fit metallicity of the ambient medium found with this model is $Z = 1.7 \pm 0.2$ times the solar metallicity, and the best-fit CR source spectral index is $s = 1.9^{+0.5}_{-0.6}$ (see Fig. 3). The latter parameter is consistent with the expectation that the nonthermal particles are produced by the diffusive shock acceleration process. We found that the CR power needed to explain the intensity of the nonthermal X-ray emission amounts to $(0.5–1.8) \times 10^{39}$ erg s^{-1}. In comparison, a to-

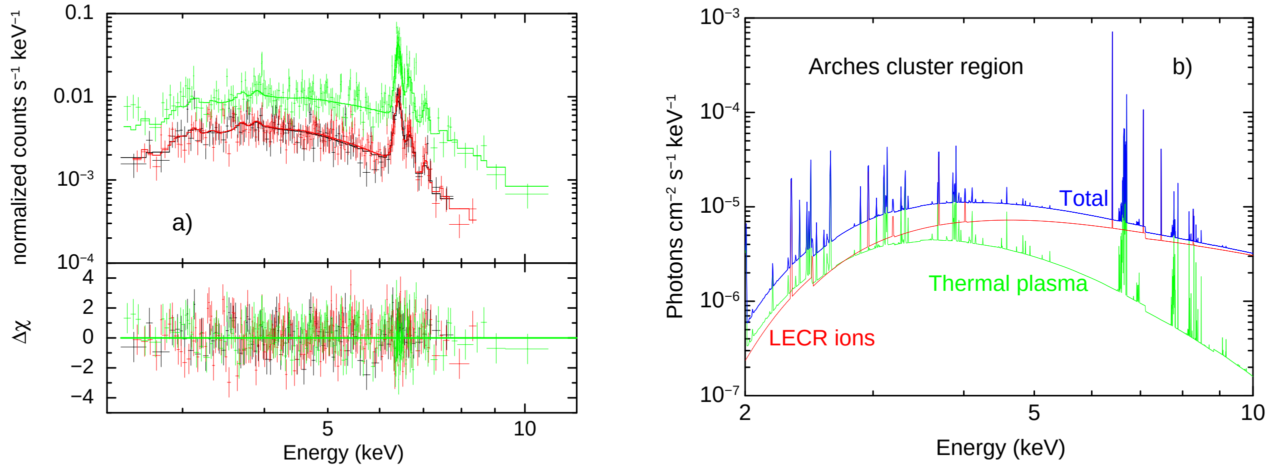

Figure 3: **a)** *XMM-Newton*/EPIC MOS and pn spectra of the bright emission surrounding the Arches cluster (see Fig. 2 and Ref. [21]) and the best-fit spectral model assuming that the emission comes from a combination of a collisionally ionization equilibrium plasma (APEC model) and a nonthermal component produced by interactions of LECR ions with a molecular cloud; **b)** model components.

tal kinetic power of $\sim 2.3 \times 10^{40}$ erg s^{-1} is currently processed in the ongoing supersonic collision between the star cluster and the molecular cloud emitting the 6.4 keV line, such that a particle acceleration efficiency of a few percent in this system would be enough to explain the X-ray luminosity.

4 Conclusions

Recent observations with *XMM-Newton* and *Chandra* strongly suggest that the bulk of the 6.4 keV line emission from the GC region is related to the past activity of the supermassive black hole Sgr A^*. But the apparently non-variable 6.4 keV line radiation from the Arches cluster region is different and it could be produced by LECR ions. The kinetic energy associated with the measured proper motion of the star cluster could account for a large population of accelerated ions in the cluster vicinity. Deeper observations of this region with X-ray and infrared telescopes would allow better characterization of the acceleration process and the effects of LECRs on the interstellar medium.

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