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Synchrotron emission from a nearby zone of Sgr A*

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ABSTRACT

Quasi-linear diffusion (QLD), driven by cyclotron instability, is proposed as a mechanism for the possible generation of synchrotron emission in the nearby zone of Sgr A*. For physically reasonable parameters, QLD, by causing non-zero pitch angle scattering, lets electrons with relativistic factors of the order of 10^8 emit synchrotron radiation in the hard X-ray spectral band ∼120 keV.

Key words: black hole physics – radiation mechanisms: non-thermal – galaxies: general.

1 INTRODUCTION

Very high energy (VHE) astronomy research took some giant strides in the last decade. The diffuse VHE electromagnetic radiation from the central black hole of the Milky Way, observed by the High Energy Stereoscopic System (HESS) Collaboration (Abramowski et al. 2016), showed γ-rays with a photon index of ∼2.3 and energies extending to the TeV range. Such VHE photons are likely to be generated via hadronic pp channels. This discovery has opened a door for additional study of a mechanism responsible for the generation of VHE particles, their sources like Sagittarius A* (Sgr A*), and the consequent radiation. It is clear that energetic particles/emission pump energy from the preponderant gravitational field, but pinpointing a specific mechanism is still a matter of discussion; some possible contenders are models of diffusive acceleration (Siming, Melia & Petrosian 2006), the Langmuir–Landau centrifugal drive (Mahajan et al. 2013; Osmanov, Mahajan & Machabeli 2017), and magnetospheric gap acceleration (Katsoulakos, Rieger & Reville 2020).

Recent studies have established that the X-ray band (Snowden et al. 1997; Ponti et al. 2017; Mossoux et al. 2020) in the radiation emission from Sgr A* might have a synchrotron origin. Therefore, let us examine the role of synchrotron emission in the generation of X-rays. Because the magnetic field close to the central black hole (BH) is strong, synchrotron emission from electrons is expected to be very efficient. Consequently, the particles very rapidly lose their transversal momentum (the component perpendicular to the magnetic field line) and fall to the ground Landau level, terminating the emission.

Let us estimate the expected time for the duration of emission. Remembering the synchrotron emission power of a single relativistic electron, $P_s \simeq 2e^4B^2\gamma^2/(3m^2c^3)$, one can show that for physical parameters typical for the magnetosphere of Sgr A* (including $B \sim 10$ G, Osmanov et al. 2017), and the corresponding cooling time-scale $t_s = \gamma mc^2/P_s$, the electrons with a relativistic factor $\gamma = 10^6$ will cease to radiate in ∼2.6 s.

Compare this to the kinematic time-scale of ∼190 s (two orders of magnitude larger), the latter being the rotation period of the central BH $P = 2\pi/\Omega$, where $\Omega \simeq ac^3/(GM)$ is the angular velocity of the nearby area of the BH. Here we have used the following parameters of Sgr A*: $a \simeq 0.65$ (Dokuchaev 2014) and $M \simeq 4 \times 10^6$ $M_\odot$ (Gillessen et al. 2009) ($M_\odot$ is the solar mass).

One must further note (Siming et al. 2006; Osmanov et al. 2017; Katsoulakos et al. 2020) that for (much) higher particle energies, the synchrotron cooling time-scale will be even shorter. One has to emphasize that considerably higher Lorentz factors $\sim10^{10}$ are possible, for example, in an equilibrium scenario where the (centrifugal) acceleration time-scale, $t_{acc} \simeq \frac{1}{2}\Omega^{-1}\gamma^{-1/2}$, is of the order of t_s. A similar situation could pertain in a stochastic acceleration process (Siming et al. 2006), and in the gap-type acceleration mechanism (Katsoulakos et al. 2020), indicating that the perpendicular momentum via synchrotron losses vanishes very rapidly.

The preceding discussion clearly indicates that the standard synchrotron mechanism can be significant only in relatively distant regions from the BH (see the paragraph following equation 9). Of course, if there were to exist a mechanism that could restore perpendicular energy, the particle could continue emitting synchrotron radiation. One such mechanism, invoking the cyclotron instability driven by the anomalous Doppler effect (Kazbegi, Machabeli & Melikidze 1991), demonstrated that the instability-driven quasi-linear diffusion could push particles across magnetic field lines. As a result, non-zero pitch angles are preserved and the corresponding synchrotron mechanism is maintained. This mechanism has been applied to active galactic nuclei (Osmanov 2010), pulsars (Chkheidze, Machabeli & Osmanov 2011), and magnetars (Osmanov 2014) and it was shown that quasi-linear diffusion (QLD) might be a significant mechanism maintaining a continuous synchrotron emission.

The present paper, investigating the dynamics of relativistic electrons, aims to show how synchrotron emission is maintained via QLD in the magnetosphere of Sgr A*. The paper is organized as

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follows: in Section 2 we introduce the theoretical model, in Section 3 we apply the model to Sgr A* and derive the relevant results, and in Section 4 we discuss and summarize them.

2 THEORETICAL MODEL

In the rotating magnetospheres of compact objects, electron–positron plasmas may be viewed as consisting of two components: the bulk with relatively small Lorentz factors, $\gamma_{\rm p}$, and a smaller high-$\gamma_{\rm b}$ beam component (Machabeli & Usov 1979; Lominadze, Machabeli & Usov 1983). This general description naturally applies to the class of objects like the nearby zone of Sgr A* (Osmanov 2010). Close to BHs, the accretion matter has a very high temperature, resulting in full ionization of the accretion flow, creating a plasma. In the same region, efficient pair creation may take place (Laurent & Titarchuk 2018), potentially leading to the formation of an electron–positron plasma.

It was shown in Osmanov (2021) that the length-scale of the acceleration region is $\sim R_{\rm lc}/\gamma_{\rm b}$, where $R_{\rm lc} = c/\Omega$ is the radius of the light cylinder (LC), a hypothetical zone where the linear velocity of rotation equals the speed of light and $\gamma_{\rm b} \sim 10^8$. The resulting acceleration shell is very thin; one can therefore assume that the energy in this area is almost uniformly distributed among different species: $n_{\rm b}\gamma_{\rm b} \simeq n_{\rm p}\gamma_{\rm p}$. It is worth noting that, unlike the synchrotron mechanism that does not impose any significant constraints on particle dynamics, other restricting factors will lead to an equilibrium between acceleration and energy losses. It has been shown by Kazbegi et al. (1991) that in the regime of the frozen-in condition the plasma is subject to the anomalous Doppler effect, which induces unstable resonance cyclotron modes:

$$\omega - k_{_\parallel} c - k_x u_x - \frac{\omega_B}{\gamma_{\rm b}} = 0, \tag{1}$$

where $k_{_\parallel}$ denotes the longitudinal (along the magnetic field lines) component of the wavevector, k_x is the component along the drift, $u_x \approx c^2\gamma_{\rm b}/\rho\omega_B$ denotes the curvature drift velocity, c is the speed of light, ρ is the curvature radius of the magnetic field lines, and $\omega_B = eB/mc$ is the cyclotron frequency.

The cyclotron frequency corresponding to the resonance condition is given by (Malov & Machabeli 2001):

$$\nu \approx \frac{\omega_B}{2\pi\delta\gamma_{\rm b}}, \qquad \delta = \frac{\omega_{\rm p}^2}{4\omega_B^2\gamma_{\rm p}^3}, \tag{2}$$

where $\omega_{\rm p} = \sqrt{4\pi n_{\rm p} e^2/m}$ denotes the Langmuir frequency of the electron–positron plasma component; $n_{\rm p}$ is the corresponding number density.

Outside the LC zone, the dynamics is predominantly governed by accretion (Osmanov et al. 2017). Let us further assume that some fraction $\eta < 1$ of the whole kinetic energy of accretion matter is transferred to emission. One could then estimate the number density by the following expression (Osmanov et al. 2017):

$$n_{\rm p} = \frac{L}{4\eta\pi m_p c^2 \upsilon R_{\rm lc}^2}, \tag{3}$$

where m_p is the proton's mass and

$$\upsilon = c\sqrt{1 - \left(\frac{c^2}{c^2 + \frac{GM}{R_{\rm lc}}}\right)^2} \tag{4}$$

is the velocity of the accreting matter near the LC. Throughout the paper we use $\eta = 0.1$. It is worth noting that the possible maximum efficiency of energy conversion in the accretion process is of the order of 0.25 (Carroll & Ostlie 2010).

To study QLD, one should take into account two forces that take part in the diffusive distribution process. Following Landau & Lifshitz (1971), one of the dissipative forces is the synchrotron radiation reaction force,

$$F_\perp = -\alpha_{\rm s}\frac{p_\perp}{p_\parallel}\left(1 + \frac{p_\perp^2}{m^2c^2}\right), \; F_\parallel = -\frac{\alpha_{\rm s}}{m^2c^2}p_\perp^2, \tag{5}$$

where $\alpha_{\rm s} = 2e^2\omega_B^2/3c^2$ and $p_{_\parallel}$ and $p_\perp$ are the longitudinal and transversal components of the momentum.

The second force originates from the non-uniformity of the magnetic field. In particular, one can show that if the magnetic field lines are curved, the particles experience the force with the following components (Landau & Lifshitz 1971):

$$G_\perp = -\frac{cp_\perp}{\rho}, \qquad G_{_\parallel} = \frac{cp_\perp^2}{\rho p_\parallel}, \tag{6}$$

where ρ is the curvature radius of the magnetic field lines.

Under the action of these forces, the kinetic equation for the particle distribution function, f, may be written as (Lomindze et al. 1983)

$$\frac{\partial f}{\partial t} + \frac{1}{p_\perp}\frac{\partial}{\partial p_\perp}\left(p_\perp\left[F_\perp + G_\perp\right]f\right) = \frac{1}{p_\perp}\frac{\partial}{\partial p_\perp}\left(p_\perp D_{\perp,\perp}\frac{\partial f}{\partial p_\perp}\right), \tag{7}$$

where $D_{\perp,\perp} = D\delta E_k^2$ denotes the diffusion coefficient, $D = e^2/8c$ (Chkheidze et al. 2011), and $|E_k|^2$ is the corresponding wave energy density per unit of wavelength. With the plausible assumption that half of the beam's energy density, $mc^2 n_{\rm b}\gamma_{\rm b}^2$, converts to that of the waves, $|E_k|^2 k$ (Machabeli & Usov 1979; Lomindze et al. 1983), one obtains

$$|E_k|^2 = \frac{mc^3 n_{\rm b}\gamma_{\rm b}}{4\pi\nu}. \tag{8}$$

If the energy were equipartitioned between the plasma and the beam, $n_{\rm b} \simeq n_{\rm p}\gamma_{\rm p}/\gamma_{\rm b}$.

We next estimate the magnitude of the magnetic field by equating the magnetic energy density, $B^2/8\pi$, and the emission energy density, $L/4\pi r^2 c$:

$$B \simeq \sqrt{\frac{2L}{r^2c}} \simeq 27.5 \times \frac{R_{\rm lc}}{r} \times \left(\frac{L}{10^{37}\,{\rm erg\,s^{-1}}}\right)^{1/2} {\rm G}; \tag{9}$$

it is a continuously increasing function of the bolometric luminosity, but this dependence is not very sensitive. It is worth noting that the synchrotron mechanism might become significant at distances for which the cooling time-scale is large compared to the kinematic time-scale, r/c; this takes place at distances larger than $\sim 50R_{\rm lc}$, where $B \leq 0.6$ G.

Due to the very efficient synchrotron cooling process, the pitch angles are usually very small. By combining equations (5), (6), and (9) one can make a straightforward estimate for the following ratio for physically realistic parameters:

$$\frac{F_\perp}{G_\perp} \simeq 4.5 \times 10^{-7} \times \frac{L}{10^{37}\,{\rm erg\,s^{-1}}} \times \frac{\rho}{R_{\rm lc}} \times \left(\frac{R_{\rm lc}}{r}\right)^2 \times \left(\frac{\psi}{10^{-5}\,{\rm rad}}\right)^2 << 1. \tag{10}$$

From equation (10) it is clear that this condition is valid for the pitch angles satisfying $\psi \ll 0.015$ rad. Therefore, $F_\perp$ can be neglected compared to $G_\perp$ in equation (7), which, for the time-stationary case $\partial/\partial t = 0$, reduces to

$$\frac{1}{p_\perp}\frac{\partial}{\partial p_\perp}(p_\perp G_\perp f) = \frac{1}{p_\perp}\frac{\partial}{\partial p_\perp}\left(p_\perp D_{\perp,\perp}\frac{\partial f}{\partial p_\perp}\right) \quad (11)$$

leading to the solution

$$f(p_\perp) = C\exp\left(\int\frac{G_\perp}{D_{\perp,\perp}}\mathrm{d}p_\perp\right) = C\mathrm{e}^{-\left(\frac{p_\perp}{p_{\perp 0}}\right)^2}, \quad (12)$$

where $C =$ const and

$$p_{\perp 0} \equiv \left(\frac{2\rho D_{\perp,\perp}}{c}\right)^{1/2}. \quad (13)$$

Hence the average value of the pitch angle is given by

$$\bar{\psi} = \frac{1}{p_\parallel}\frac{\int_0^\infty p_\perp f(p_\perp)\mathrm{d}p_\perp}{\int_0^\infty f(p_\perp)\mathrm{d}p_\perp} \approx \frac{1}{\sqrt{\pi}}\frac{p_{\perp 0}}{p_\parallel}. \quad (14)$$

Due to the non-zero pitch angles, the relativistic particles radiate in the synchrotron regime, emitting photons with energies (Rybicki & Lightman 1979)

$$\epsilon_{\mathrm{eV}} \approx 1.2\times 10^{-8} B\gamma^2 \sin\psi. \quad (15)$$

The theoretical model that we have just established is ready to be applied to Sgr A*; the agenda is to investigate the spectral characteristics of the emission process.

3 DISCUSSION

The central black hole exhibits the characteristics of a very efficient accelerator, boosting proton energies up to the PeV level. Through a series of well defined steps, these energies can be transferred to create relativistic electrons/electron–positron plasmas. That such processes may take place in the nearby zone of Sgr A* was shown in a series of recent papers (Siming et al. 2006; Osmanov et al. 2017; Katsoulakos et al. 2020). This paper, however, assumes (without getting into the details of production) a strongly relativistic beam of electrons and investigates the associated synchrotron emission in the hard X-ray regime. One of the challenges was to find mechanisms that will allow more or less continuous synchrotron radiation. We finally settled on quasi-linear diffusion induced by cyclotron instability.

For ultra-relativistic electrons with a Lorentz factor of the order of 10^8, one can estimate the frequency of the induced cyclotron waves (see equation 2):

$$\nu \simeq 6.9\times 10^3 \times \frac{10^8}{\gamma_{\mathrm{b}}} \times \left(\frac{\gamma_{\mathrm{p}}}{2}\right)^3 \times \left(\frac{R_{\mathrm{lc}}}{r}\right)^3 \times \left(\frac{L}{10^{37}\,\mathrm{erg\,s^{-1}}}\right)^{1/2} \mathrm{Hz}. \quad (16)$$

The frequency is evidently very sensitive to the plasma γ_{p}. The frequency increases with γ_{p}, but the pitch angle, on the other hand, is a continuously decreasing function of the relativistic factor:

$$\psi \simeq 6.7\times 10^{-6} \times \left(\frac{\gamma_{\mathrm{b}}}{10^8}\right)^{1/2} \times \left(\frac{2}{\gamma_{\mathrm{p}}}\right)^{5/2} \times \left(\frac{L}{10^{37}\,\mathrm{erg\,s^{-1}}}\right)^{1/4} \times \left(\frac{r}{R_{\mathrm{lc}}}\right)^{5/2} \mathrm{rad}. \quad (17)$$

For a large enough relativistic factor, then, the pitch angle (measuring perpendicular energy) might become sufficiently small that the synchrotron emission may just shut off.

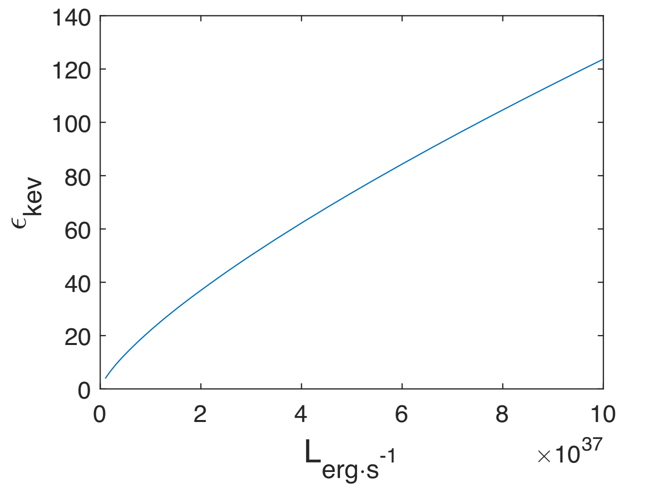

Figure 1. Emitted photon energy versus bolometric luminosity. The set of parameters is $\gamma_{\mathrm{b}} = 10^8$, $\gamma_{\mathrm{p}} = 2$, $a \simeq 0.65$, and $M \simeq 4\times 10^6\,\mathrm{M}_\odot$.

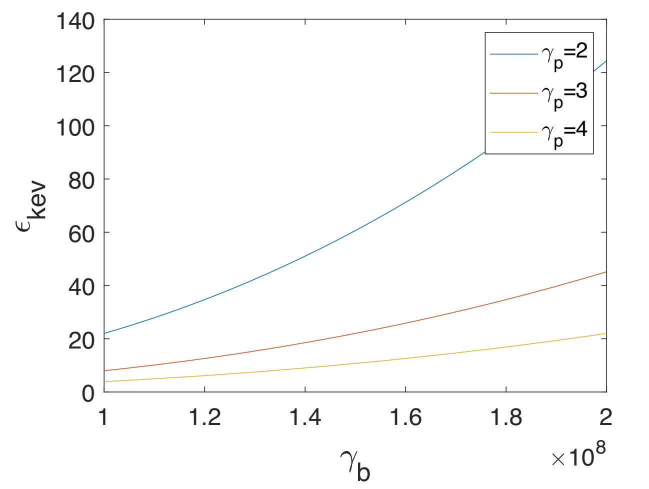

Figure 2. Plots for $\epsilon_{\mathrm{keV}}(\gamma_{\mathrm{b}})$. The set of parameters is $L = 10^{37}$ erg s^{-1}, $\gamma_{\mathrm{p}} = \{2; 4; 6\}$, $a \simeq 0.65$, and $M \simeq 4\times 10^6\,\mathrm{M}_\odot$.

For the same set of parameters the synchrotron photon energy is given by

$$\epsilon \simeq 2.2\times 10^4 \times \left(\frac{\gamma_{\mathrm{b}}}{10^8}\right)^{5/2} \times \left(\frac{2}{\gamma_{\mathrm{p}}}\right)^{5/2} \times \left(\frac{L}{10^{37}\,\mathrm{erg\,s^{-1}}}\right)^{3/4} \times \left(\frac{r}{R_{\mathrm{lc}}}\right)^{3/2} \mathrm{eV}. \quad (18)$$

In Fig. 1 we plot the dependence of photon energy ϵ on the bolometric luminosity L for the set of parameters $\gamma_{\mathrm{b}} = 10^8$, $\gamma_{\mathrm{p}} = 2$, $a \simeq 0.65$, and $M \simeq 4\times 10^6\,\mathrm{M}_\odot$. The emitted energy is in the hard X-ray band, and is a continuously increasing function of the bolometric luminosity, a natural consequence of the dependence of the magnetic field and the pitch angle on L (see equations 9 and 17).

We have already mentioned that the synchrotron photon energy is sensitive to the values of the plasma γ_{p}. In Fig. 2, plots of the emitted photon energy versus the bulk relativistic factor are shown for several values of γ_{p} for the set of parameters $L = 10^{37}$ erg s^{-1}, $\gamma_{\mathrm{p}} = \{2; 3; 4\}$, $a \simeq 0.65$, and $M \simeq 4\times 10^6\,\mathrm{M}_\odot$. We note that, by increasing the plasma Lorentz factor by a factor of two, the photon energy decreases significantly. A similar 3D plot is displayed in Fig. 3

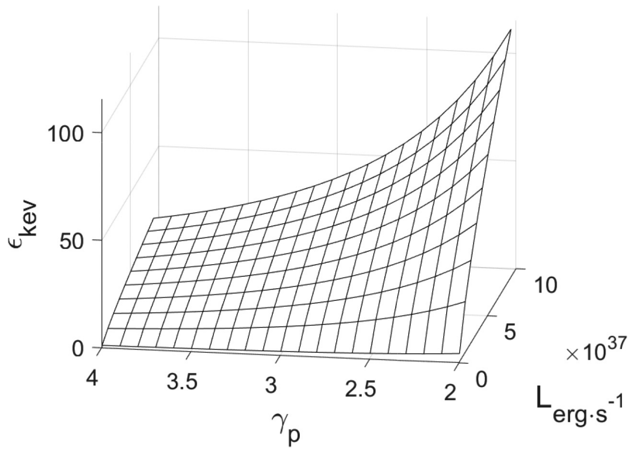

Figure 3. 3D plot of the photon's energy versus γ_p and L.

where, apart from the γ_p dependence, we highlight how the photon energy depends on the bolometric luminosity. The set of parameters is the same as in Fig. 1, except γ_p, which varies over the range [2–4].

This analysis shows that, despite strong synchrotron losses in the nearby area of the central BH of the galaxy, QLD maintains a continuous synchrotron emission process and might account for the generation of hard X-rays.

4 SUMMARY

Perhaps the most significant contribution of this paper is to demonstrate how instability-induced QLD extends the times over which synchrotron emission may be maintained even for very high-γ electrons. For this purpose, the kinetic equation governing the particle distribution by pitch angles was derived.

For physical parameters typical of the magnetosphere of Sgr A*, it had already been found that the anomalous Doppler effect causes cyclotron instability with a frequency of the order of 10^4 Hz, which means that this particular mode cannot escape a thick plasma ambient of the BH. It is precisely these waves that, via QLD, 'restore' the synchrotron process by diffusively injecting the perpendicular electron energy.

With QLD creating the right conditions for continuing synchrotron emission for typical γ_p bolometric luminosities, one could safely expect photon energies up to 120 keV lying in the hard X-ray spectral band.

DATA AVAILABILITY

Data are available in the article and can be accessed via a DOI link.

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