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In situ acceleration in the Galactic Center Arc

S. Lieb, H. Lesch, and G. T. Birk

Institute for Astronomy and Astrophysics, University of Munich, Scheinerstr 1, 81679 Munich, Germany

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Abstract. For the nonthermal radio emission of the Galactic Center Arc in situ electron acceleration is imperative. The observed radio spectrum can be modeled by a transport equation for the relativistic electrons which includes particle acceleration by electric fields, momentum diffusion via scattering by magnetohydrodynamical turbulence and energy losses by synchrotron radiation. The accelerating electric fields can be regarded as a natural consequence of multiple reconnection events, caused by the interaction between a molecular cloud and the Arc region. The radio spectrum and even the recently detected 150 GHz emission, explicitely originating from the interaction regions of a molecular cloud with the magnetized Arc, can be explained in terms of quasi-monoenergetically distributed relativistic electrons with a typical energy of about 10 GeV accelerated in stochastically distributed magnetic reconnection zones.

Key words. Galaxy: center – acceleration of particles – radio continuum: ISM

1. Introduction

The Galactic Center (GC) Arc is a unique nonthermal radio continuum structure in the Galaxy. It is located at a projected distance of about 30 pc from the Sgr A complex and consists of a network of magnetic filaments filled with relativistic electrons running almost perfectly perpendicular to the Galactic plane (e.g. Yusef-Zadeh et al. 1984). The nonthermal nature of these filaments has been proven beyond any doubt by radio emission which exhibits a degree of linear polarization which is close to the intrinsic value at high frequencies of 60% (Reich et al. 1988; Lesch & Reich 1992). We emphasize the nonthermal character of the Arc since its radio spectrum is a very remarkable one. A decomposition of its radio spectrum between 843 MHz and 43 GHz by (Reich et al. 1988) shows a spectral index $\alpha = +0.3$ (we use the conventional relation that the observed flux S_ν scales as ν^α). This finding of an increasing radio spectral index has been confirmed by high resolution VLA-observations (Anantharamaiah et al. 1991).

Such an inverted radiation spectrum with an index of +0.3 is expected from a quasi-monoenergetic electron distribution or an energy distribution with a well-defined low energy cutoff, respectively (Lesch et al. 1988). Observations at high frequencies (between 32 GHz, Lesch & Reich 1992, and 43 GHz, Sofue et al. 1987b) seem to indicate a spectral turn over, i.e. a fading of the Arc towards higher frequencies. However, Reich et al. (2000) detected an enhanced emission at 150 GHz slightly offset relative to the most intense vertical nonthermal filaments seen at lower frequencies. This emission originates from the apparent interacting areas of dense molecular material with the Arc. 150 GHz emission was also detected south of a molecular cloud, where the vertical filaments of the Arc cross a weak filamentary structure. The spectrum of the emission is inverted relative to 43 GHz and compatible with an origin from quasi-monoenergetic electrons or an electron distribution with a low energy cutoff, but not with optically thin emission from cold dust. Reich et al. (2000) conclude "that the coincidence of enhanced emission with regions of interacting molecular gas strongly suggests that high-energy electrons are accelerated in those places where the magnetic field is compressed". They calculated a Lorentz factor of the electrons to be $\gamma \simeq 2 \times 10^4$ emitting synchrotron radiation at 150 GHz within a magnetic field of 1 mG.

To summarize, in the Galactic center several areas appear to be filled with relativistic electrons whose energy must be distributed quasi-monoenergetically around a few GeV. We note that even the very center of our Galaxy Sgr A* exhibits a radio to infrared spectrum which is in surprisingly good agreement with optically thin synchrotron emission of a quasi-monoenergetic electron distribution with a typical energy of 80 MeV, i.e. Lorentz factor of 160 (Duschl & Lesch 1994).

In a former paper about particle acceleration in the Arc (Lesch & Reich 1992) we considered the magnetohydrodynamical interaction of a molecular cloud with the Arc filaments. Especially we investigated the role of the moving gas cloud as a trigger mechanism for magnetic field amplification accompanied by dissipation of the magnetic energy via magnetic reconnection.

Magnetic reconnection takes place when magnetic field lines with antiparallel directions encounter. Such a situation corresponds to the formation of an electric current sheet. Typically astrophysical plasmas are ideal electric conductors,

Send offprint requests to: S. Lieb,
e-mail: lieb@usm.uni-muenchen.de

i.e. their electrical conductivity is very high. In such media the magnetic field is frozen into the motion of the conducting fluid. Any plasma velocity distortion onto the magnetic field lines is automatically related to an electric field which is perpendicular to the plasma velocity and the magnetic field. This electric field is described by the ideal Ohm's law

$$\boldsymbol{E} + \frac{1}{c}\boldsymbol{v} \times \boldsymbol{B} = 0. \tag{1}$$

In a plasma where the magnetic field is strongly distorted by shear flows, radial explosive flows or stochastic motions, it is unavoidable that field lines with antiparallel directions encounter. Consequently, the ideal conducting plasma switches into a nonideal medium with a finite, localized electrical conductivity, i.e. the ideal form of Ohm's law is violated. The strong spatial gradients of the magnetic field in such interaction zones represent an energetic "crisis" which is relaxed by partial dissipation of the magnetic energy via the formation of current sheets in the resistive medium (e.g. Priest & Forbes 2000, and references therein). The nonideal Ohm's law is given by

$$\boldsymbol{E} + \frac{1}{c}\boldsymbol{v} \times \boldsymbol{B} = \boldsymbol{R} \neq 0, \tag{2}$$

where $\boldsymbol{R}$ is some yet unspecified nonideal term, i.e. the plasma resistance.

In other words, magnetic reconnection corresponds to a magnetic field aligned electric field which is associated with a generalized electric potential (Schindler et al. 1988, 1991)

$$V = -\int E_{\rm s}\,{\rm d}s = -\int R_{\rm s}\,{\rm d}s \tag{3}$$

where the integral is evaluated along the magnetic field lines that penetrate the reconnection region. Of course, such a potential drop offers the possibility to accelerate particles very efficiently (Schindler et al. 1991; Blackman 1996; Lesch & Birk 1997; Lesch & Birk 1998; Schopper et al. 1998; Litvinenko 1999; Nodes et al. 2003).

Instead of investigating the acceleration in one reconnection zone, we consider in this contribution the acceleration of relativistic electrons in numerous reconnection regions, i.e. current carrying filaments driven by the interaction of a molecular cloud with the magnetic field in the Galactic Center Arc (Lesch & Reich 1992; Serabyn & Morris 1994). This scenario arises quite naturally, since the necessary energy source is represented by moving molecular gas which encounters the poloidal magnetic fields in the Arc which is proven to be present by the observed very high polarization of the radio emission up to 60%.

Since we have many acceleration regions we apply a dynamical description of the energy distribution function of relativistic electrons based on systematic momentum gains by reconnection, losses by synchrotron losses and momentum diffusion due to scattering on magnetohydrodynamical turbulence, i.e. Alfvén waves and magnetosonic waves.

2. The temporal evolution of the energy distribution function of relativistic particles

The dynamical evolution of a population of high-energy particles that do not interact with each other is described by the Liouville equation

$$\frac{\partial F}{\partial t} + \frac{{\rm d}\boldsymbol{r}}{{\rm d}t}\nabla_{\boldsymbol{r}}F + \frac{{\rm d}\boldsymbol{p}}{{\rm d}t}\nabla_{\boldsymbol{p}}F = 0 \tag{4}$$

where $F(\boldsymbol{r}, \boldsymbol{p}, t)$ is the one-body distribution function. Due to the complexity of the non-linear dynamics in 6+1 dimensions this equation is only of limited use. Fortunately, for our purposes we do not need to know the full information of the particle dynamics. Rather, we will make use of the following assumptions. First, we will assume pitch angle isotropy. This should be granted by efficient particle scattering in momentum space in reconnection regions caused by Alfvénic and magnetosonic wave fields with relatively high-energy densities (see Schlickeiser 1986). Second, we are interested in the global energy spectrum of the radiating electrons and thus, can dispense with the detailed spatial dependence of the distribution function.

Consequently, we deal with the isotropic distribution $f(p,t) = \int {\rm d}\boldsymbol{r}F(\boldsymbol{r},\boldsymbol{p},t)/V$ where V denotes the emission volume. The total particle number is calculated as $N(t) = 4\pi \int f p^2 {\rm d}p$. The continuous momentum gains and losses Δp of the particles can be described by the momentum operator

$$\mathcal{L}_p = \frac{1}{p^2}\frac{\partial}{\partial p}\left[(\dot{p}_{\rm gain} + \dot{p}_{\rm loss})p^2\right], \tag{5}$$

where the systematic temporal momentum gains and losses are denoted by $\dot{p}_{\rm gain}$ and $\dot{p}_{\rm loss}$, respectively.

Additionally, we will allow for stochastic diffusion in momentum space by scattering of magnetohydrodynamical fluctuations (in the sense of a Fokker-Planck term) denoted by D_p. In principle, catastrophic losses that may result to a further sink in the balance equation for f can be modeled by a characteristic time τ, i.e. $\partial f/\partial t \sim -f/\tau$. Finally, the injected particle population is represented by some explicit source term $S(p)$. Accordingly, the temporal evolution of the particle distribution is governed by the equation (Schlickeiser 1984, 1986)

$$\frac{\partial f(p,t)}{\partial t} - \frac{1}{p^2}\frac{\partial}{\partial p}\left(D_p p^2 \frac{\partial f(p,t)}{\partial p}\right) + \mathcal{L}_p f(p,t) + \frac{f(p,t)}{\tau} = S(p) \tag{6}$$

which holds, if the distribution function $f(\boldsymbol{r}, p, t)$ is separable in space and momentum, and if the momentum operator $\mathcal{L}_p$ does not depend on the spatial coordinates. In the present application based on the reconnection scenario (see also Birk et al. 2001) the momentum gain is given by $\dot{p}_{\rm gain} = \frac{\rm d}{{\rm d}t}(\gamma m v) = qE_{\rm s} = \zeta =$ const., where γ denotes the Lorentz factor, $E_{\rm s}$ is the accelerating electric field component (locally directed parallel to the magnetic field) and q is the electrical charge.

We emphasize that the acceleration of high-energy particles is regarded as a consequence of the conversion of magnetic field energy into particle energy by magnetic reconnection. Since synchrotron losses are responsible for the observed non-thermal radio emission from the Arc we take $\dot{p}_{\rm loss} = -kp^2$ with $k = \frac{4}{3}\sigma_{\rm T}U_{\rm B}/m_{\rm e}^2c^2$, with the Thomson cross section $\sigma_{\rm T}$, the electron mass m_e, the speed of light c and the magnetic field energy density U_B. For our applications inverse Compton scattering, which has the same γ-dependence as synchrotron losses, as well as bremsstrahlung are negligible. In case of particle scattering in momentum space by Alfvénic waves the momentum diffusion coefficient is given (Schlickeiser 1984) by $D_p = Dp^2$ with $D = v_A^2/9K(p)$, where v_A is the Alfvén velocity and $K(p) = \lambda c\beta/3$ is the spatial diffusion coefficient, which has been expressed in terms of the particle's mean free path λ (Schlickeiser 1986). For our purpose we have set $\beta = v/c = 1$. Since we have to model the formation of monoenergetic distribution functions, the effect of catastrophic losses must be negligible, because otherwise the particles would leave the acceleration region before a pile up in energy has been established (Schlickeiser 1986).

3. Numerical results

In order to calculate the temporal evolution of $f(p, t)$ by numerical integration of Eq. (6) we first have to specify the physical parameters ζ, k, D, and $S(p)$, which are related to the physical conditions of the Galactic Center Arc. First of all, we discuss the source term $S(p)$. Since the energy distribution of the injected particles, which are generated in the Galactic center, is a monoenergetic one (Lesch & Reich 1992), the use of a δ-like source term, represented, e.g., by a $\cosh^{-4}(p)$-function in our calculations, is a reasonable assumption. As a typical injection energy we use 75 MeV, the value close to the one calculated by (Duschl & Lesch 1994) for the central object Sgr A*, i.e. $\gamma_{inj} = 150$.

The magnetic field strength in the arcs filaments is of the order of a few mG, or higher (Yusef-Zadeh & Morris 1987a). To be on the save side we use the 150 GHz detection of (Reich et al. 2000) close to the Arc as the maximum synchrotron frequency emitted. Thus, we have to deal with a Lorentz factor of about $\gamma \simeq 2\times10^4$, necessary for 150 GHz synchrotron emission in a magnetic field of 10^{-3} G.

The maximum electric field strength is given by $E \simeq w/cB$, where w denotes the bulk velocity of the thermal plasma that acts as an MHD generator. The detected cloud motion is in the range of 15−45 km s^{-1} (Tsuboi et al. 1997). Again to be on the save side we will use $v = 5$ km s^{-1} which gives a maximum electric field strength of 10^{-8} statvolt cm^{-1}. If we assume, that electrons can be accelerated over the whole extension of the Arc (about 40 pc) without energy losses (ideal linear accelerator), we need a minimum strength of the average electric field of $E_s \simeq 3 \times 10^{-13}$ statvolt cm^{-1} to reach the observed particle energies, which is a tiny fraction of the available electric field.

This oversimplification is helpful to work out the analysis with a reference value of ζ and is not meant as a physical assumption we apply (see discussion below).

If we restrict our calculations to electrons we obtain an estimate for the systematic acceleration term

$$\dot{p}_{gain} = eE_s = \zeta \geq 1.5 \times 10^{-22} \text{ dyne}. \quad (7)$$

Due to the high polarization of the synchrotron radiation, up to 60% (Lesch & Reich 1992) we consider only synchrotron emission to be responsible for the energy losses of the particles in the Arc. In this case we can find a certain value $p_0 = (3\zeta m_e^2 c^2/4\sigma_T U_B)^{1/2}$ where momentum gains and losses keep the balance. For momenta $p > p_0$ momentum loss dominates momentum gain. For momenta $p < p_0$ the opposite holds. Thus, we expect a pile up for the distribution function $f(p, t)$ at p_0, which is consistent with a monoenergetic distribution of the electrons (see also Lesch & Reich 1992). As discussed above, the pile up in the Arc should occur at momenta with Lorentz factor $\gamma \simeq 2 \times 10^4$. If one assumes, for simplicity, a constant electric field of $E_s \simeq 3 \times 10^{-13}$ statvolt cm^{-1} over the complete expansion of the arc, a magnetic field of 3×10^{-3} Gauss is necessary for a pile up at $p_0 = \gamma m_e c = 5.4 \times 10^{-13}$ g cm s^{-1} according to a systematic loss coefficient of

$$k = \frac{4}{3}\sigma_T \frac{U_B}{m_e^2 c^2} = 1.4 \times 10^3 \text{ g}^{-1} \text{ cm}^{-1}. \quad (8)$$

However, the particles, in fact, will be accelerated locally in numerous reconnection regions with $E_\parallel \neq 0$ and will be scattered by magnetohydrodynamic fluctuations like Alfvénic and/or magnetosonic waves. Consequently, the electric field strength in the reconnection regions must be ultimately stronger than 10^{-13} statvolt cm^{-1}. Indeed, the electric field can be estimated by the ratio of the number density of relativistic electrons n_r and the thermal electron density n_e (Papadopoulos 1977)

$$\frac{n_r}{n_e} \simeq \exp\left[-\frac{E_c}{2E}\right]. \quad (9)$$

$E_c \simeq m_e v_{the} \nu_{coll}/e$ denotes the critical electric field, whereas v_{the} is the thermal velocity of the electrons and ν_{coll} is the collision frequency. As calculated by Lesch & Reich (1992) the thermal electron number density n_e in the Arc filaments is about 10 cm^{-3} and the density of relativistic electrons is of the order of 10^{-7} cm^{-3}. If we use an electron temperature of 10^4 K we obtain from Eq. (9) $E \simeq 3 \times 10^{-10}$ statvolt cm^{-1}, which can be easily achieved by the available electric field, induced by the $\boldsymbol{w} \times \boldsymbol{B}$ -motion of a molecular clouds calculated above.

To obtain the diffusion coefficient D we first have to estimate the particle's mean free path λ. As shown in (Schlickeiser 2002) λ can be determined by

$$\lambda \simeq r_G \left(\frac{B_0}{\delta B}\right)^2 \left(\frac{L_0}{r_G}\right)^{q-1} \quad (10)$$

where r_G is the gyro radius of the protons, $B_0/\delta B$ gives the ratio between macroscopic and fluctuated magnetic field strength, L_0 is the expansion of the considered object and q is turbulence spectral index. In the vicinity of a strong magnetic distortion, like the Arc filaments, Burgers turbulence is expected to be excited (Chambers et al. 1988). Thus, we choose a turbulence spectral index of $q = 2$. With a particle density of $n \sim 10$ cm^{-3} and a magnetic field strength of 3×10^{-3} Gauss the Alfvénic velocity is about 700 km s^{-1}. Hence we obtain for the diffusion coefficient

$$D = \frac{v_A^2}{3c\lambda} \simeq \frac{1}{3}\left(\frac{\delta B}{B_0}\right)^2 \frac{v_A^2}{cL_0} = 5.4 \times 10^{-18} \text{ s}^{-1}, \quad (11)$$

if we assume, that $B_0/\delta B$ is of the order of 10 which implies a reasonable level of well-developed turbulence. Much higher diffusion coefficients would inhibit pile-up distributions. However, a quasi-linear theory applied for Eq. (9) requires $\delta B < B_0$.

The synchrotron emission spectrum associated with the particle spectrum can be calculated from (Rybicki & Lightman 1979)

$$I_\nu = \int P_\nu(p) N(p)\,\mathrm{d}p, \tag{12}$$

where

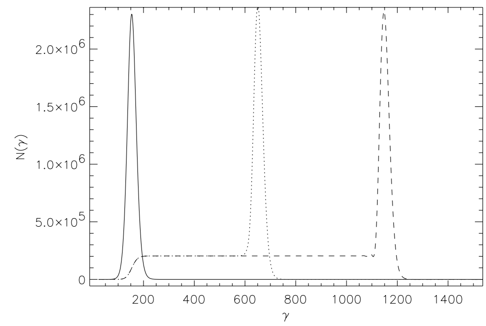
$$P_\nu(p) = \frac{2\sqrt{3}}{3}\frac{e^2 m_{\mathrm{e}}^2 c\nu}{p^2}\int_{\nu/\nu_{\mathrm{c}}}^{\infty} K_{\frac{5}{3}}(\xi)\,\mathrm{d}\xi, \tag{13}$$

is the power per unit frequency ν emitted by each electron. $K_{\frac{5}{3}}(\xi)$ denotes the modified Bessel function of the second kind and $\nu_{\mathrm{c}} = 3\gamma^3\omega_{\mathrm{G}}/4\pi$ is the critical frequency (ω_{G} is the electron gyro frequency).

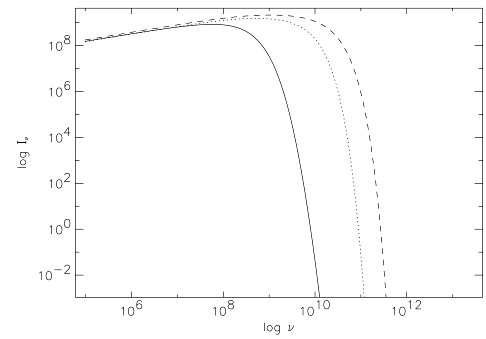
Having clarified the initial conditions and chosen physical parameters we now come to the numerical results. Figure 1 shows the temporal evolution of the particle density $N(\gamma)$ and the corresponding synchrotron emission spectrum, calculated from Eq. (12). In the chosen normalization the time is measured by $t_0 = 10^9$ s. As long as the particle acceleration exceeds the synchrotron losses, the quasi-monoenergetic distribution of the electrons is shifted toward higher momenta (a, c). Due to momentum diffusion the maximum of $N(\gamma)$ decreases with time (c). As soon as the synchrotron losses are comparable to the energy gains, the maximum of $N(\gamma)$ increases again (Fig. 2a). At a Lorentz factor of about $\gamma = 2 \times 10^4$ the momentum gains and losses are balanced and the distribution of the electrons that are assumed to be contained in the Arc during the entire radiation processes develops towards a shifted pile up. Consequently, a monoenergetic distribution function evolves again (Fig. 2c). The cut-off frequency remains almost constant during entire pile-up dynamics. The associated radiation spectrum (Fig. 2c) corresponds to the one observed by several authors, including the 150 GHz emission detected by (Reich et al. 2000). We note that for a finite loss time of $\tau \leq 10^{10}$ s the pile-up is prevented by the particle losses.

4. Conclusions

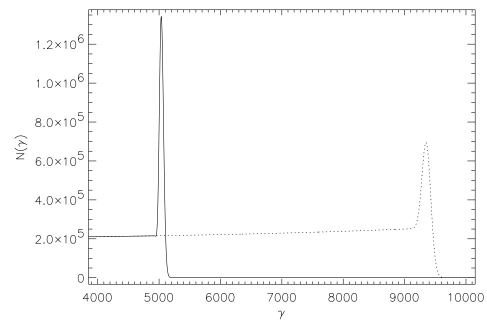
In the filaments of the Galactic Center Arc electrons are accelerated to considerably high energies of about 10 GeV. This is obvious from the detected polarized radio emission exhibiting a very high degree of polarization (60%) and a rising spectrum with a spectral index of +0.3 up to 150 GHz. Such a spectral behavior is due to an energy distribution function of the radiating relativistic electrons which either has a low-energy cutoff or which is quasi mononenergetic. No obvious energy sources for particle acceleration are present in the neighborhood of the filaments. The very center of the galaxy, SgrA* is a source for monoenergetic relativistic particles but on significant lower energies of about 50 MeV (Duschl & Lesch 1994). However,



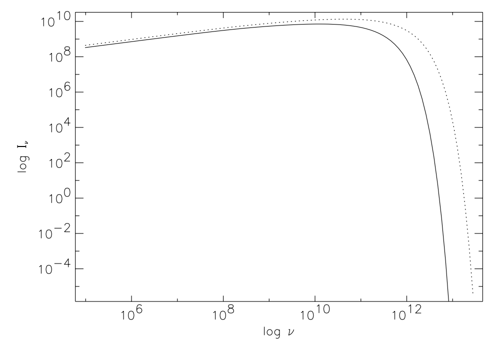
a) Temporal evolution of $N(\gamma)$. The solid, dotted and dashed lines show the injected particle spectrum and the evolution after $t = 1\,t_0$ and $t = 2\,t_0$, respectively.



b) The corresponding synchrotron spectrum I_ν.

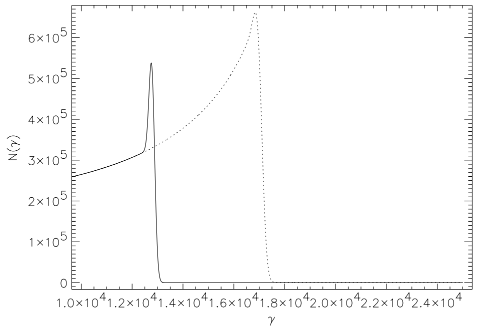


c) Temporal evolution of $N(\gamma)$. The solid and dotted lines show the evolution after $t = 10\,t_0$ and $t = 20\,t_0$, respectively.

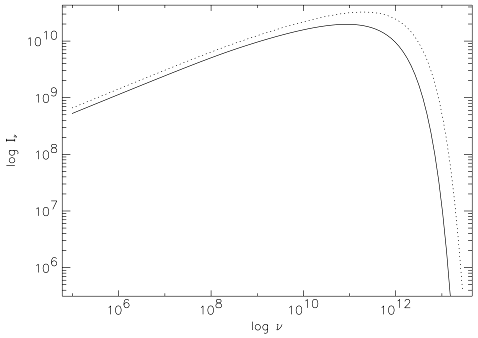


d) The corresponding synchrotron spectrum I_ν.

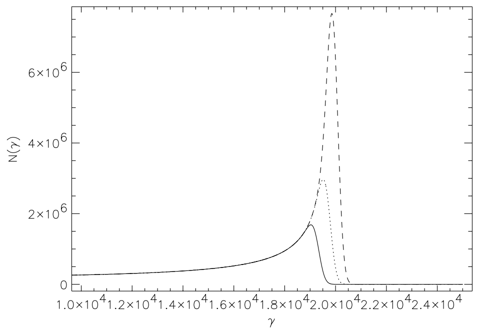
Fig. 1. Temporal evolution of $N(\gamma)$ calculated from Eq. (6). The values of the physical parameters, which we have used for our calculations are: $\zeta = 1.5 \times 10^{-22}$ dyne, $k = 1.4 \times 10^3$ $\mathrm{g}^{-1}\,\mathrm{cm}^{-1}$ and $D = 5.4 \times 10^{-18}$ s^{-1}. To evaluate the synchrotron emission spectrum (see Eq. (12)) we have used a magnetic field strength of $B = 3$ mG.



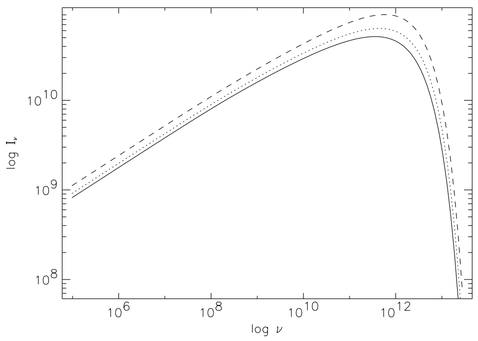
a) Temporal evolution of $N(\gamma)$. The solid and dotted lines show the evolution after $t = 30\,t_0$ and $t = 50\,t_0$, respectively.



b) The corresponding synchrotron spectrum I_ν.



c) Temporal evolution of $N(\gamma)$. The solid, dotted and dashed lines show the evolution after $t = 80\,t_0$, $t = 100\,t_0$ and $t = 150\,t_0$, respectively.



d) The corresponding synchrotron spectrum I_ν.

Fig. 2. Temporal evolution of $N(\gamma)$ towards a quasi-monoenergetic distribution function **a)**, **c)**. The resulting synchrotron emission spectrum **d)** shows an inverted spectrum with a spectral index of $\alpha = 1/3$ ($I_\nu \sim \nu^\alpha$) and a cutoff-frequency of some hundred GHz after 1.5×10^{11} s.

the magnetic filaments interact with the plasma of a molecular cloud which moves with velocities of some 10 km s^{-1} relative to the magnetic field. This interaction can be interpreted in terms of the induced Lorentz force inducing a convective electric field which in the first place is oriented perpendicular to the magnetic field and the local plasma velocity of a molecular cloud. The motion of the plasma locally distorts the magnetic field necessarily in such a way that antiparallel directed field lines encounter. Provided that some violation of ideal Ohm's law occurs, e.g. due to microturbulence, magnetic reconnection will occur. The magnetic field energy will be partly converted to particle energization. In the reconnection regions a magnetic field-aligned electric field component forms with a magnitude of some fraction of the convective electric field. This parallel electric field represents a perfect candidate for efficient particle acceleration. The required electric field for the electron energization are considerably weaker than the magnetic field which is in accordance with the observational fact that the cloud plasma moves with velocities much lower than the speed of light. Since reconnection is a localized phenomenon which depends on the local properties of the plasma, we consider a scenario characterized by multiple reconnection sheets in which particles are accelerated and scattered by magnetohydrodynamical fluctuations. Such scattering leads to diffusion in energy space. Moreover, we take into account the energy losses by the observed synchrotron radiation. By means of a relatively simply transport equation for the distribution function of the radiating relativistic electrons we could show that an injected monoenergetic distribution function with 75 MeV (coming from the Galactic center) evolves into a quasi-monoenergetic distribution function at 10 GeV. The resulting radiation spectra increase with frequency up to some hundred GHz according to the observations, i.e. $S_\nu \sim \nu^{1/3}$.

A major assumption of our study is the complete isotropy of the distribution function which is based on calculations by (Achatz et al. 1990), who show that the isotropisation time $t_{\rm iso} = c/v_{\rm A}(B/\delta B)1/\Omega$, where Ω is the gyro frequency of the protons. In this application $t_{\rm iso}$ is about 4×10^6 s which is much shorter than the studied time scale of the evolution of the distribution function. Some non-isotropic particle population would lead to an overlap of a second radiation component in a specific energy range that we can not handle in our model. However, the present observations seem to give no hint to such a component.

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