Jets and gamma-ray emission from isolated accreting black holes

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ABSTRACT
Isolated black holes (IBHs) are not usually considered to be important astrophysical sources, since, even in the case of a high accretion rate, an accretion disc rarely can be formed due to the small angular momentum of the infalling matter. Thus, such systems are not expected to feature thermal disc emission which makes the dominant contribution to the radiative output of binary systems harbouring a BH. Moreover, due to their relatively modest accretion rates, these objects are not conventionally treated as feasible jet sources. However, the large number of IBHs in the Galaxy, estimated to be $\sim 10^8$, implies a very high density of $10^{-4} \text{pc}^{-3}$ and an average distance between IBHs of $\sim 10 \text{pc}$. Our study shows that the magnetic flux, accumulated on the horizon of an IBH because of accretion of interstellar matter, allows the Blandford–Znajeck mechanism to be activated. Thus, electron–positron jets can be launched. We have performed 2D numerical modelling which allowed the jet power to be estimated. Their inferred properties make such jets a feasible electron accelerator which, in molecular clouds (MCs), allows electron energy to be boosted up to $\sim 1 \text{ PeV}$. For the conditions expected in MCs, the radiative cooling time should be comparable to the escape time. Thus, these sources can contribute both to the population of unidentified point-like sources and to the local cosmic-ray (CR) electron spectrum. The impact of the generated electron CRs depends on the diffusion rate inside MCs. If the diffusion regime in a MC is similar to Galactic diffusion, the produced electrons should rapidly escape the cloud and contribute to the Galactic CR population at very high energies, $> 100 \text{ TeV}$. However, due to the modest jet luminosity (at the level of $\sim 10^{35} \text{erg s}^{-1}$) and low filling factor of MCs, these sources cannot make a significant contribution to the spectrum of CR electrons at lower energies. On the other hand, if the diffusion within MCs operates at a rate close to the Bohm limit, the CR electrons escaping from the source should be confined in the cloud, significantly contributing to the local density of CRs. The inverse Compton emission of these locally generated CRs may explain the variety of gamma-ray spectra detected from nearby MCs.

Key words: accretion, accretion discs – ISM: clouds – ISM: jets and outflows – local interstellar matter – gamma-rays: ISM.

1 INTRODUCTION

The Galactic population of isolated compact objects – remnants of massive star evolution – is very large: about $10^9$ (see e.g. Sartore & Treves 2010, and references therein). It should be dominated by neutron stars, but the number of isolated black holes (IBHs) is also non-negligible: their number is $\gtrsim 10^8$ (Agol & Kamionkowski 2002). Taking into account this large number, the local spatial density of IBHs can be high, corresponding to a typical distance to the closest objects $\sim$ tens of parsec. Such estimates are usually based on detailed calculations for isolated neutron stars and normalization based on the relative number of compact objects. The local isolated neutron star spatial density is estimated to be $\sim 3 \times 10^{-5}$ to $3 \times 10^{-4} \text{pc}^{-3}$ (Popov et al. 2005; Ofek 2009; Sartore & Treves 2010). The relative number of BHs to neutron stars is about 1/3. Then, the local density of IBHs can be taken as $\sim 10^{-5} - 10^{-4} \text{pc}^{-3}$.

Historically, the first ideas about the detectability of IBHs were related to accretion from the interstellar medium (ISM) (Shvartsman 1971). Detailed studies concluded that accreting IBHs must emit mostly in X-rays and the infrared (IR) (see e.g. Fujita et al. 1998). Calculations of the observability of the population of Galactic...
accreting IBHs were performed several times (see e.g. Popov & Prokhorov 1998, and references therein). One of the most detailed studies was presented by Agol & Kamionkowski (2002). Despite several attempts (Chisholm, Dodson & Kolb 2003), up to now no firm candidates for accreting IBHs (or for accreting isolated neutron stars, see Treves et al. 2000) are known. Optimistically, future space missions may discover them (Grindlay et al. 2009).

The only possible detections of IBHs reported in recent years are related to microlensing. About 10 years ago several candidates were reported by different research groups (Agol et al. 2002; Bennett et al. 2002; Mao et al. 2002). Recent calculations (Sartore & Treves 2010) predict that further compact objects will be detected via microlensing.

To understand IBHs better, it is very important to seek examples of these not related to microlensing events. There is a discovery potential for IBHs via modelling of disrupted massive binaries (Prokhorov & Popov 2002), or in a close examination of unidentified objects with peculiar properties among different surveys. In this note, we develop the idea of Barkov & Khangulyan (2012) who proposed that BHs with spherical accretion, that is, without the formation of an accretion disc (see also Komissarov & Barkov 2009), can be sources of relativistic jets powered by rotating BHs (Ruffini & Wilson 1975; Lovelace 1976) or, for example, the Blandford–Znajek (BZ) mechanism (Blandford & Znajek 1977). These jets form conditions for efficient acceleration of non-thermal particles which can radiate energetic electrons, with quite low luminosity in X-ray and other energy bands. Strict limits on the energy release rate in X-rays $L_X < 10^{-3}$ (in units of the Bondi–Hoyle accretion rate with efficiency $0.1 c^2$) were achieved in the work of Motch & Pakull (2012), which is complementary to the scenario suggested by Barkov & Khangulyan (2012).

In the following two sections, we briefly describe the model. Then, in Section 4 we present our results on the possible observational appearance of IBHs. Finally, we present some discussion and our conclusions.

### 2 Jets from IBHs

Recently, it was shown that the BZ mechanism can be activated in the case of direct wind accretion on to a rotating BH in a close binary system (Barkov & Khangulyan 2012). Thus, a relatively powerful jet, with kinetic luminosity of $\sim 10^{35} \text{ erg s}^{-1}$, can be launched in systems which do not feature an accretion disc. A similar situation may arise in the case of accretion of the ISM on to an IBH. Accretion from the ISM has been studied for many decades starting from the seminal papers by Bondi (1952) and Bondi & Hoyle (1944) (see a review in Edgar 2004). The case of IBHs was studied by Shvartsman (1971) and later this approach was developed by Beskin & Karpov (2005) and Beskin et al. (2008).

In the simplest case, the accretion rate can be estimated as

$$\dot{M} = \lambda 4\pi \frac{(GM)^2 \rho}{v^3}. \quad (1)$$

Here $\dot{M}$ is the mass of an accretion source, $\rho$ is the density of the surrounding medium (the ISM density in our case) and $\lambda$ is a dimensionless coefficient $\leq 1$. The velocity $v$ must include the contribution from different types of motion. The most important

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1 In a different astrophysical context, jets from charged IBHs were also studied by Punsly (1998a,b), Punsly (1999), Punsly et al. (2000) and Torres et al. (2001) (see also Maccarone 2005).
where $\Psi_1 = \Psi/10^{17}$ is magnetic flux in units of $10^{17}$ G cm$^2$. The function $f(a) = a^2 (1 + \sqrt{1 - a^2})^{-2}$ is a dimensionless function accounting for the BH rotation. Combining equations (5) and (6) and adopting $f(a) \approx 0.1$ (or $a \sim 0.5$), one can derive the magnetic flux value on the BH horizon, required for the optimal operation of the BZ mechanism:

$$\Psi_{BZ} \approx 3 \times 10^{18} M_{1/2}^2 M \text{ G cm}^2.$$  (7)

The value of $\Psi$ which an IBH can accumulate by Bondi accretion is $\Psi_{B} = 2 R_{BH}^2 \rho_{ISM}$ or

$$\Psi_{B} \approx 3 \times 10^{22} R_{BH}^2 \rho_{ISM} - 6 \text{ G cm}^2.$$  (8)

Therefore, in the case of accretion of the ISM matter on to an IBH, the BZ mechanism can achieve its optimal performance provided by equation (5). However, we note that there are some uncertainties related to the role of the reconnection and magnetic flux escape from the horizon of an IBH.

Thus, for the expected accretion rates, the IBH might be characterized by a jet with a luminosity of $L_{\text{ice}} \sim 10^{31}$ erg s$^{-1}$, $L_{\text{ib}} \sim 10^{30}$ erg s$^{-1}$ and $L_{\text{acc}} \sim 10^{35}$ erg s$^{-1}$ for the cases of BHs located in the LIC, LB and MCs, respectively. Given the dependence of the jet luminosity on different factors, for example, the accretion rate, magnetic field at the horizon, and spin and velocity of the IBH, these luminosities can be, in fact, considered as upper limits.

### 3 Spatial Density of IBHs

Another important issue is related to the actual number of such IBHs in the ISM with different properties. For the above estimates, there should be $N_{\text{BH}} = 4 \times (10^{-1} - 10^{-5}) R_1^3$ located within $R = 10 R_1$ pc from the Solar system. For the expected size of a LIC of $\approx 10$ pc, this yields a probability of 4–40 per cent for a BH to be located there. With increasing $R$ the number of BHs rises rapidly achieving $10^{12}$ inside $\sim 1$ kpc. On the other hand, IBHs in high-density regions are rare: they are at least two orders of magnitude less frequent than BHs in the normal and low-density ISM. A typical MC with $M \sim 10^3 M_\odot$ has a volume $\sim 10^8$ pc$^3$, that is, for an IBH spatial density close to the Galactic plane, $\sim 10^{-11}$ pc$^{-3}$, we expect one IBH per cloud. On larger scales, the number of BHs located in MCs might be very significant. Given, however, the presence of pulsars on this scale, the impact of IBHs is negligibly small. For example, the Vela pulsar is located at a distance of 290 pc, and is expected to be a powerful source of cosmic-ray (CR) leptons with power comparable to its spin-down luminosity, $L_{\text{sd}} = 7 \times 10^{36}$ erg s$^{-1}$ (see e.g. Hinton et al. 2011, and references therein). The closest IBH in a cloud is expected at a distance $\sim 170$–$200$ pc (see the list of nearby MCs, e.g. in Dame et al. 1987). Up to $\sim 300$ pc only approximately five IBHs are expected to be located in MCs.

### 4 Observational Appearance of IBH Jets

#### 4.1 Particle acceleration

Non-thermal processes in BH jets can be linked to shocks at the head of the jets. A system consisting of two shocks is expected to be formed: a forward shock propagating through the ISM and a relativistic reverse shock in the jet matter. These shocks are characterized by very different velocities. Properties of the non-thermal particles accelerated by these shocks may differ significantly thereafter. The jet power and medium density determine the key properties of the forward shock. Namely, the jet ram pressure should be balanced by the inertia of the ISM. This yields the following relation:

$$L_j = \frac{p_{sh}}{\rho v^2} R_5^2 C,$$

where $\rho v$ and $R_5$ are the jet ram pressure and the radius of the termination shock, respectively. The latter can be estimated as

$$R_5 \approx 3 \times 10^{15} L_{j,1/2} R_{1/2} v_{1/2}^{1/2} \text{ cm}.$$  (9)

An upper limit on the forward shock magnetic field strength can be derived from pressure balance $B_j^2/8 \pi \rho \lesssim p_{sh}$:

$$B_j \approx 15 \rho^{1/2} v_1.5 \mu G.$$  (10)

The reverse shock in the jet has a similar size and, in fact, its magnetic field strength should be comparable. Indeed, since jets launched by the BZ mechanism are magnetically dominated, the magnetic field strength can be estimated as

$$B_\perp = \frac{4 L_{\text{rel}}}{c R_5}.$$  (11)

This allows one to obtain the following relation:

$$B_j R_5 = 10^{11} M_{1/2} v_{1.5}^{1/2} R_{2/3} C_{-1} G \text{ cm}.$$  (12)

For the shock size $R_5$ determined by equation (9), this yields a magnetic field of

$$B_j = 10 \rho_{-2/3} v_1.5 \mu G,$$

which is quite close to the strength expected at the forward shock (equation 10). The main difference between these two shocks is related to the efficiency of the acceleration process.

The acceleration time of non-thermal particles can be estimated as

$$t_{\text{acc}} = \frac{\eta R_5}{c},$$  (14)

where $R_5$ is the electron gyroradius and $\eta > 1$ is a dimensionless parameter, which in the case of diffusive shock acceleration has a value of $\eta_{\text{diff}} = 2 \pi (c/v_\text{sh})^2$. In the case of the forward termination shock, it is natural to assume that $v_\text{sh} \approx v$. In the case of the reverse shock, which is expected be characterized by relativistic velocities, the value of the $\eta$ parameter is not defined in the framework of theoretical models. However, from the interpretation of the non-thermal emission detected from the Crab nebula, one can infer that in the relativistic case $\eta < 100$, thus in what follows, we will assume $\eta_{\text{rel}} = 10$.

In the case of diffusive shock acceleration, the maximum energy of the non-thermal particles can be limited either by the loss rate or by the confinement requirement. The latter is referred to as the Hillas criterion (Hillas 1984), which for the Bohm diffusion regime (i.e. the diffusion coefficient is $D \sim R_5 c$) can be formulated as a limitation of the size of the acceleration site $R_{\text{acc}}$:

$$R_{\text{acc}} > R_5 \sqrt{\eta}.$$  (15)

In the asymptotic case, $\eta = 1$ so this condition results in an obvious requirement of $R_{\text{acc}} > R_5$. Since in the case of jet termination $R_{\text{acc}} \sim R_5$, the electrons can be accelerated up to

$$E_{\text{max},i} < 5 C_{-1} \rho_{-2/3}^{1/2} M_{1/2} v_1.5 \text{ GeV}.$$  (16)

This value gives $\approx 2$ GeV for the local cloud, and $\sim 0.5$ GeV for a BH located in the LB. In the case of a BH in a MC, the maximum energy...
achieved at the jet termination shock is $\sim 200$ GeV. Therefore, the jet forward termination shock is not a plausible acceleration site for any reasonable conditions.

Regarding the reverse shock, the Hills criterion gives the following estimate:

$$E_{\text{max},s} < 30C_{1/2}M_1^{1/2}v_{1,5}^{3/2}n_1^{-1/2} \text{TeV}.$$  \hspace{1cm} (17)

This gives $\sim 10$ TeV for the local cloud, and $\sim 1$ TeV for the BH located in the LB. In the case of an IBH in a MC, the maximum energy of particles accelerated at the jet termination shock is $\sim 1$ PeV.

4.2 Source emission

The acceleration process is limited by the Hills criterion; therefore, the particles are not expected to lose all their energy in the source. Nevertheless, we compare the radiation cooling time to the particle escape time. The latter depends on the regime of diffusion inside the source. Obviously, this diffusion rate is different from the Galactic diffusion coefficient used to derive equation (27) and it cannot be determined from first principles. However, the X-ray properties of supernova remnants apparently indicate that inside these shock-related non-thermal sources, the diffusion regime is similar to the Bohm limit (Aharonian 2004). We therefore assume this diffusion regime to be valid inside the source. Thus, the source escape time can be estimated as

$$t_{\text{bd}} = 5 \times 10^3 E_{\text{TeV}}^{-1/2} v_{1,5}^{-4} \rho_{-24}^{1/2} \text{s}.$$ \hspace{1cm} (18)

Moreover, we note that the assumption of Bohm diffusion inside the source is in fact closely related to the acceleration rate assumed above.

The radiative cooling time is determined by the density of the corresponding target. In the case of the synchrotron and inverse Compton (IC) radiation mechanisms on the magnetic field, $\epsilon_B = B^2/8\pi$, and photon energy densities $\epsilon_{ph}$,

$$t_{\text{rad}} = 3 \times 10^5 (\epsilon_{ph}/1 \text{ eV cm}^{-3})^{-1} E_{\text{TeV}}^{-1/2} \text{yr},$$ \hspace{1cm} (19)

and in the case of the synchrotron cooling

$$t_{\text{syn}} = 4 \times 10^3 (B/5 \mu \text{G})^{-2} E_{\text{TeV}}^{-1/2} \text{yr}.$$ \hspace{1cm} (20)

Equations (10) and (13) allow the synchrotron cooling time to be obtained, and the IC cooling time can be estimated based on the size of the termination shock. Jet kinetic energy is largely transformed to thermal energy at the termination shock. The photon energy density inside the source can be estimated as $\epsilon_{ph} \approx L_j/2\pi R_{j}^2 c \sim 3\rho_{-24}v_{1,5}^{-1} \text{ eV cm}^{-3}$, which is comparable to the magnetic field energy density: $\epsilon_B \sim 5\rho_{-24}v_{1,5}^{-1} \text{ eV cm}^{-3}$. Thus, assuming that IC scattering operates in the Thomson regime, we can estimate the radiative cooling time as

$$t_{\text{rad}} = 1.5 \times 10^5 \rho_{-24}^{1/2} v_{1,5}^{-2} E_{\text{TeV}}^{-1/2} \text{s}.$$ \hspace{1cm} (21)

The lower energy part of the spectrum, $E < 1$ GeV, is dominated by bremsstrahlung losses

$$t_{\text{bd}} = 6 \times 10^3 \rho_{-24}^{1/2} \text{yr}.$$ \hspace{1cm} (22)

The non-thermal particles emit in the source a fraction of their energy, which depends on the ratio of the diffusion to radiative cooling times:

$$L_{\text{ph}} \sim \frac{t_{\text{bd}}/t_{\text{rad}}}{1 + t_{\text{bd}}/t_{\text{rad}}} \chi L_j.$$ \hspace{1cm} (23)

where $\chi$ is the fraction of the jet kinetic luminosity which is transferred to the population of the non-thermal particles. The estimate given by equation (23) depends strongly on the density of the surrounding medium:

$$t_{\text{bd}}/t_{\text{rad}} = 3 \times 10^{-3} \rho_{-24}^{-1/2} v_{1,5}^{-2}.$$ \hspace{1cm} (24)

It can be seen that for the case of the density of the medium expected in MCs, that is, $\rho \sim 10^{-21} \text{ g cm}^{-3}$, this estimate approaches unity. Thus, while in the cases of the LB and LIC, jets emerging from IBHs are not expected to be plausible point sources, in the case of an IBH accreting in a MC, non-thermal particles can emit a significant part of their energy in the close vicinity of the source.

One should expect similar fluxes emitted through the synchrotron and IC channels, since the energy densities of the target fields are similar. However, these components are located in different energy bands. The synchrotron emission should be emitted at an energy

$$\epsilon_{\text{syn}} = 10v_{1,5}^{1/2} E_{\text{TeV}}^{1/2} \text{ eV},$$ \hspace{1cm} (25)

where $E_{\text{TeV}}$ and $\rho_{-21}$ are the energy of the emitting particle in TeV units and density of the MC in $10^{-21} \text{ g cm}^{-3}$ units. For the assumed condition at the reverse shock electron energy can significantly exceed 1 TeV (see equation 16); thus, the synchrotron emission can cover quite a broad range from the radio to soft gamma-rays.

The main target for the IC scattering is provided by the shocked MC material, which is expected to be heated to $\sim 50$ K. In the Thomson limit, the energy of the upscattered photon can be estimated as

$$\epsilon_{\text{ic}} = 20E_{\text{TeV}}^2 \text{ GeV}.$$ \hspace{1cm} (26)

The transition to the Klein–Nishina regime occurs for electrons of energy $\geq 20$ TeV, that is, in the band which is slightly above the range of optimal sensitivity of modern Cherenkov detectors. Thus, in what follows we do not discuss this energy range. It is also worthy to note that the spectral shape is expected to be flat with photon index $\sim 2$, without any significant breaks. Indeed, since the dominant cooling processes – synchrotron and IC – and escape time have the same energy dependence, the spectral breaks can be induced either by the transition to bremsstrahlung cooling dominance or by the age of the source. The latter is not relevant for sources with age $> 10^4$ yr, and the bremsstrahlung break should appear in the synchrotron spectrum at energy $< 1$ GHz, that is, in the range that can hardly be probed with observations.

However, if the diffusion deviates significantly from the Bohm regime, it may lead to modification of the spectral shape, and a break in the electron spectrum should appear at energy corresponding to $t_{\text{esc}} = t_{\text{rad}}$. Also a weak Klein–Nishina hardening (see e.g. Khangulyan & Aharonian 2005; Moderski et al. 2005) is expected to appear in the X-ray energy band, $\epsilon_{\text{syn}} \sim 10$ keV.

4.3 Particle cooling and diffusion in the ISM

Since even in the case of IBHs located in MCs a significant fraction of the non-thermal power is able to escape from the source, below we study whether these sources can produce a detectable contribution to the diffuse background. However, the total power of these sources per kpc$^3$ is $\sim 10^{46} \text{ erg s}^{-1} \text{ kpc}^{-3}$; this is approximately two orders of magnitude below the rate required to power the CR electron spectrum (see e.g. Aharonian 2004). Therefore, these sources can give an important contribution only in the high-energy part of the spectrum, where more distant sources are heavily suppressed due to particle energy losses.

Following previous studies (Dwek et al. 1997; Strong, Moskalenko & Reimer 2000; Porter et al. 2008) we can say that the Galactic background radiation field in the solar vicinity...
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5 DISCUSSION AND CONCLUSIONS

In this paper, we examine IBHs as possible jet sources. We find that the non-thermal efficiency of these sources depends strongly on the density of the surrounding medium. IBH jets launched in high-density environments are characterized by a larger power and a stronger magnetic field. The latter feature appears to be very important since (1) it allows non-thermal particles to be accelerated up to very high energy; and (2) the ratio of the escape time to radiative cooling time decreases with increase of the magnetic field. The key source parameters (jet luminosity, maximum energy of non-thermal particles, and non-thermal luminosity) scale with density as \( L_j \propto \rho \), \( E_{\text{max}} \propto \rho^{1/2} \) and \( L_{\text{th}} \propto \rho^{5/2} \). The strong dependence of the non-thermal power, \( L_{\text{th}} \), on the medium density is related to the change of the ratio of radiative to escape losses and, in the case of high enough density, converges to the fast cooling regime, where \( L_{\text{th}} \propto L_j \propto \rho \).

More specifically, if the density of the surrounding medium is high, \( \rho \gtrsim 10^{-21} \text{ g cm}^{-3} \), the radiation cooling time is shorter than the escape time (if the Bohm diffusion regime is applied within the source). Thus, the jet reverse shock can turn into an efficient emitter of non-thermal radiation. On the other hand, if the density is lower, \( \rho \lesssim 10^{-21} \text{ g cm}^{-3} \), the IBH should act as a source of electrons CRs, interestingly, for conventional values of the MC density (\( \rho \sim 10^{-21} \text{ g cm}^{-3} \)), the non-thermal power of these sources should be shared in comparable fractions between the radiative cooling inside the source and escape losses. Finally, for the IBHs accreting in low-density environments, \( \rho \ll 10^{-21} \text{ g cm}^{-3} \), the accretion rate and maximum available energy of non-thermal particles appear to be too low to make any detectable contribution to the CR spectrum. Moreover, as fast particles escape these sources, they should not be considered as feasible point-like emitters.

As discussed above, in the case of accretion in a high-density medium, the jets launched by IBHs may emit a significant fraction of the accreted energy through synchrotron (from the radio to soft gamma-rays) and IC channels (up to very high energies) within \( 10^{16} \text{ cm} \) from the jet termination point. The luminosities radiated via these two mechanisms should be similar, since the energy densities of the target fields are expected to be comparable.

The dominant target photon field for the IC is expected to be provided by shocked MC matter, which should be heated to \( T \sim 50 \text{ K} \). Because of this relatively low temperature of the target field, the Klein–Nishina effect may lead to a weak hardening of the synchrotron X-ray component (see e.g. Khangulyan & Aharonian 2005; Mosderski et al. 2005). Thus, the spectra are expected to be featureless, with a photon index of \( \sim 2 \) over a broad energy range. Any stronger spectral features in the spectrum would be attributed to a deviation of the escape rate from the Bohm diffusion regime. It is also important to note that one can expect a certain variability of the non-thermal flux caused by the inhomogeneous structure of MCs (see e.g. Kaplan & Pikel’Ner 1979). For a typical velocity of \( 30 \text{ km s}^{-1} \), these inhomogeneities should lead to variability on a year time-scale.

For the expected non-thermal luminosity of \( <10^{38} \text{ erg s}^{-1} \), such sources should be detectable with modern X-ray and gamma-ray instruments up to a distance of \( \sim 1 \text{ kpc} \). Within this distance \( \sim 10 \) IBHs should be located in MCs. This may provide a feasible interpretation for some unidentified gamma-ray sources.

Regarding the impact of the non-thermal particles escaped from the shock region generated by IBHs in MCs, there are certain uncertainties related to the diffusion of these particles. Namely, the propagation of such particles may proceed very differently within and outside the MC. If the diffusion coefficient in the MC is comparable to the Galactic one, then the high-energy particles should rapidly escape from the MC (the MC crossing time is \( \sim 300 \text{ yr} \)). However, several uncertainties do not allow us to claim IBHs to be the best candidates for production of very high CR electrons. The distribution of spins of IBHs is unknown and if \( \alpha < 0.3 \) jets will be weak or simply not launched at all (Komissarov & Barkov 2009; Barkov & Komissarov 2010). Nevertheless, we have checked the contribution from the nearby pulsars up to a distance 300 pc using the Australia Telescope National Facility pulsar catalogue (Manchester et al. 2005). We can conclude that the contribution in the CR electron spectrum from close pulsars is about a factor of 10 smaller than the expected contribution from IBHs. Although we can miss some pulsars if their beamed radiation does not cross the Earth, such pulsars can contribute to the population of electrons near the Sun. So far it is unlikely that IBHs are the main source of electrons in CRs, except hypothetical particles with \( E > 100 \text{ TeV} \).

However, the physical scenario should be quite different if in MCs the diffusion operates slower. For example, for the Bohm diffusion regime, the particles’ confinement in MCs should be very long, \( \sim 10^7 \text{ yr} \). Thus, the non-thermal particles injected by a IBH should produce a diffusive emission component associated with the
host MC. The luminosity of this component should be comparable to the non-thermal power of the source, that is, \( <10^{35} \text{erg s}^{-1} \), so it might give a contribution comparable to the fluxes produced by CRs interacting with the MC material (Aharonian 2001; Casanova et al. 2010). Importantly, the spectra produced by CR protons interacting with the MC should be quite different from the IC spectra generated by the local population of CR electrons. Thus, this scenario can contribute to our understanding of the variety of the GeV spectra obtained from different MCs with Fermi/LAT (Yang & Aharonian, in preparation).

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