ELSEVIER

Astroparticle Physics 16 (2002) 265–270

Astroparticle Physics

www.elsevier.com/locate/astropart

UHECR production by a compact black hole dynamo: application to Sgr A*

Amir Levinson [a,*], Elihu Boldt [b]

[a] School of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel
[b] Laboratory for High Energy Astrophysics, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

Received 12 December 2000; received in revised form 12 February 2001; accepted 14 February 2001

Abstract

The possibility that the excess cosmic ray (CR) flux near 10^{18} eV, reported recently by the AGASA group, is due to a compact black hole dynamo associated with the Sgr A* source is considered. Under the assumption that the Galactic center black hole rotates with nearly maximal spin, and that the magnetic field threading the horizon is in rough equipartition with matter accreted by the hole, the spectra and total fluxes of accelerated CRs and their associated curvature emission depend only on accretion rate. For the accretion rate estimated on the basis of observations of stellar winds near Sgr A* ($\sim 10^{-3}$ Eddington), the maximum proton energy achievable by this mechanism is of the order of 10^{18} eV, and the corresponding CR power is $\sim 10^{41}\alpha_{CR}$ erg s^{-1}, where $\alpha_{CR} \ll 1$ is the CR production efficiency. The corresponding spectrum of curvature photons peaks at around 100 GeV, with a total luminosity comparable to the CR power released. For much lower accretion rates both the CR and gamma-ray fluxes predicted are completely insignificant. Upcoming gamma-ray experiments, such as CANGAROO, HESS and GLAST, can be used to probe the parameters of this system.

PACS: 98.70.Rz; 95.70.Sa
Keywords: Cosmic rays; Gamma rays; Galactic center

1. Introduction

Recent analysis of data from AGASA [1] and SUGAR [2] have indicated an excess of cosmic ray (CR) intensity over a narrow energy range around 10^{18} eV, that has been interpreted as due to a strong CR source in the direction of the Galactic center. The analysis by the AGASA group suggested a rather extended source in the general vicinity of the Galactic center, with the most significant excess obtained for a signal beam size of about 20°. Close examination of the SUGAR data [2], that was motivated by the results of the AGASA group, confirmed the existence of an excess CR flux near the direction of the Galactic center, but indicated a signal that appears to be consistent with a point source offset by about 7.5° from the true Galactic center. Clay [3] suggested that the point-like excess is caused by neutrons produced as a result of conversions of particles in a target located outside their acceleration site; in order to reach Earth before decaying, the neutrons should have energies in excess of $\sim 10^{18}$ eV. This naturally explains the absence of an excess at

* Corresponding author.
E-mail address: levinson@wise1.tau.ac.il (A. Levinson).

0927-6505/02/$ - see front matter
PII: S0927-6505(01)00116-5

energies below 10^{18} eV. The absence of an excess at energies well above that is attributed to an upper limit on the acceleration energy in the source. Clay (see also Ref. [4]) also proposed that the propagation of the charged (non-converted) particles through the Galactic magnetic field might give rise to the more extended source that appears in the AGASA data. Using detailed numerical simulations and reasonable models for the Galactic magnetic field he studied the propagation of protons from the vicinity of the Galactic center to Earth, and concluded that a source of protons near the Galactic center would be unobservable at energies below 10^{18} eV, but should produce a halo of energy dependent size and location above this energy. The details depend on the magnetic field model adopted, but in general there should be a systematic shift of the source image to the north, owing to the regular field component.

The above considerations motivated us to explore the application of a model, developed recently to explain the origin of the highest energy CRs detected [5], to the Galactic center black hole, Sgr A*. In this model the ultra-high energy CRs (UHECRs) are accelerated by the electric potential difference generated by spinning supermassive black holes associated with dormant AGNs. The model assumes that those black holes were either formed with critical angular momentum or spun up during an earlier phase when the AGNs were active, and are presently rotating with nearly maximal spins. The basic picture envisaged is that a small number of particles injected into the gap are being accelerated to ultra-high energies during episodes when the emf induced by the hole dynamo is not shorted out; in this picture the rotational energy of the hole is liberated essentially in the form of UHE particles and their associated curvature emission [6], rather than powerful jets, as seen in blazers. This is consistent with the expectation that spontaneous breakdown of the vacuum should not occur in those systems [6]. For the range of parameters relevant to UHECR production, the curvature losses suffered by the accelerating particles are severe, suppressing the maximum energy they can achieve substantially [6,7]. The curvature photons are emitted predominantly in the TeV band, with an average flux per UHECR source that exceeds the detection limit of current TeV experiments [6], and is conceivably highly variable. The total power needed to be extracted from an average UHECR source in order to account for the measured CR flux above the GZK cutoff is rather small, less than about 0.1% of the maximized Blandford–Znajek (BZ) power. Why this process is so inefficient as compared with the process of jet formation in blazers is yet an open issue. As argued by Punsley and Coroniti [8] the BZ power extracted from a BH should be governed by the process of plasma injection in the ergosphere. So perhaps in the UHECR sources, for which spontaneous vacuum breakdown as in blazers is not expected, plasma injection is considerably suppressed, resulting in a much lower efficiency.

Recent numerical simulations [9] suggest that the accretion process and magnetic field structure in the vicinity of the horizon should be non-stationary, owing to rapid magnetic field reconnection. This would probably lead to appreciable complications of the (over) simplified model adopted in Ref. [5]. For instance the location of the gap and, perhaps, the voltage drop across it might change with time, as well as the injection of seed particles into the gap. How should this affect the picture described above is unclear at present. Despite of all the complications anticipated, we shall proceed by using the simple model [5] outlined above.

2. Application to Sgr A*

There are essentially three important parameters that determine the CR and gamma-ray fluxes produced by the black hole dynamo: the mass of the hole, its angular momentum, and the strength of the magnetic field threading the horizon. In the case of Sgr A* the mass is known to a reasonably good accuracy from dynamical measurements. The other two parameters, however, are highly uncertain. Upper limits on the power and spectral peak energy of emitted CRs can be obtained if the hole angular momentum is taken to be near its critical value, and the magnetic field is assumed to be in equipartition with the matter accreted into the black hole. Under these circumstances the results depend only on one parameter, namely the accretion rate $\dot{m}$, henceforth measured in Eddington units ($L_{\rm Edd}/c^2$). Below we adopt the estimate of Eckart and Genzel [10] for the black hole mass: $M = 2.5 \times 10^6 M_\odot$.

The rate at which the Galactic black hole is accreting is unfortunately unknown. The total luminosity associated with Sgr A* is of order 10^{37} erg s^{-1} (see Ref. [11]). If we naively relate this luminosity to accretion from a standard thin disk with say 10% efficiency, we obtain $\dot{m} \sim 10^{-7}$. This value is well below those estimated by Melia [12] ($\dot{m} \sim 10^{-1.5}$) and Genzel et al. [13] ($\dot{m} \sim 10^{-3}$), based on observations of stellar winds in the vicinity of Sgr A* and assuming Bondi accretion (that might be irrelevant if the infalling matter possesses angular momentum). Narayan et al. [11] constructed an ADAF model for Sgr A* in an attempt to reconcile the low luminosity of Sgr A* with the relatively high accretion rates estimated by Melia and Genzel et al. A viable fit of the spectrum of Sgr A* by the ADAF model (but cf. Ref. [14] for a different interpretation) appears to be consistent with the measured mass of Sgr A*, with an accretion rate of $\dot{m} \sim 10^{-3}$, and with an equipartition magnetic field, provided the parameter δ is sufficiently small ($\delta \sim 10^{-3}$), where δ represents the fraction of turbulent energy that is tapped for electron heating. However, it has been subsequently shown [15] that models with large δ and considerable mass loss rate via winds [16], for which only a small fraction of the inflowing matter ultimately reaches the black hole, are also in agreement with observations. Thus, it seems that there is, at present, a large uncertainty in the value of $\dot{m}$, but that it is likely to lie in the range $10^{-7} < \dot{m} < 10^{-3}$.

The strength of the equipartition magnetic field depends, quite generally, on the details of the inflow pattern in the vicinity of the horizon. A rough estimate gives $B_4 \simeq 61(\dot{m}/M_6)^{1/2}$, where $M_6 = M/10^6 M_\odot$ [5]. This is in good agreement with the mean equipartition field calculated using the self-similar ADAF model by Narayan and Yi [17]. For Sgr A* ($M_6 = 2.5$) we obtain

$$B_4 \simeq 38\dot{m}^{1/2}. \tag{1}$$

The emf generated by a rotating black hole is given approximately by $\Delta V \sim 4.5 \times 10^{17}(a/M)(h/R_g)^2 B_4 M_6$ V. Taking $a = M$, $h = R_g$, $M_6 = 2.5$, and using Eq. (1) yields

$$\Delta V \simeq 5 \times 10^{19}\dot{m}^{1/2} \text{ V}. \tag{2}$$

For the range of $\dot{m}$ considered here (10^{-7}–10^{-3}) the emf given by the last equation lies in the range between about 10^{16} and 1.5×10^{18} V.

The energy change per unit length of an accelerating particle of charge Z and energy $\epsilon = \gamma m_i c^2$ can be expressed as [6],

$$\frac{d\epsilon}{ds} = \frac{eZ\Delta V}{h} - \frac{2}{3}\frac{e^2 Z^2 \gamma^4}{\rho^2}, \tag{3}$$

where ρ is the mean curvature radius of magnetic field lines in the gap. The first term on the r.h.s of the last equation accounts for the energy gain owing to the acceleration by the gap electric field, and the second term accounts for the losses due to curvature radiation. Under the assumption that ρ is independent of the particle's energy, Eq. (3) can be solved analytically. The maximum energy achievable, $\epsilon_{\max}$, can then be obtained by integrating Eq. (3) over the gap (i.e., from $s = 0$ to h), and is given implicitly by,

$$\ln\frac{1+x}{1-x} + 2\tan^{-1}(x) = 4\eta^{-1}. \tag{4}$$

Here $\eta = 3\mu(a/M)^{-3/4} M_6^{-1/2} Z^{-5/4} B_4^{-3/4} (\rho/R_g)^{1/2} \times (h/R_g)^{-7/4}$, with μ being the mass of the ion in units of the proton mass, is the suppression factor defined in Eq. (5) of Ref. [6] for $a = M$, and $x = \epsilon_{\max}/\bar{\epsilon}_{\max}$, where $\bar{\epsilon}_{\max}$, given explicitly in Eq. (4) of Ref. [6], is the maximum acceleration energy in the limit of large suppression (i.e., strong curvature losses), as can be readily seen from Eq. (4) wherefore $x \sim 1$ when $\eta \ll 1$. In the opposite limit, $\eta \gg 1$, the solution to Eq. (4) is given to a good approximation by $\epsilon_{\max} \simeq eZ\Delta V$, as expected. For the parameters adopted above we find

$$\eta \simeq 0.12\mu Z^{-5/4}\dot{m}^{-3/8}, \tag{5}$$

where it has been assumed that $\rho = h = R_g$.

The maximum rotational power that can be extracted from a Kerr black hole is given roughly by $L_{\rm BH} \sim 10^{40}(a/M)^2 M_6^2 B_4^2$ erg s^{-1}. We suppose that a fraction $\alpha_{CR} \ll 1$ of this power is liberated in the form of CRs. Taking again $a = M$, and using Eq. (1), we find that the CR power released by the Galactic BH can be written as

$$L_{CR} \sim 10^{44} \alpha_{CR} \dot{m} \text{ erg s}^{-1}. \quad (6)$$

The relative production efficiency of curvature photons, defined as the ratio of the total curvature loss per nucleus and the maximum energy gain, can now be expressed as

$$\kappa \equiv \frac{(Ph/c)}{\epsilon_{max}} \simeq 0.5 Z^5 B_4^3 \mu^{-4} (\epsilon_{max}/eZ\Delta V)^3$$
$$\simeq 8 \times 10^4 Z^5 \mu^{-4} \dot{m}^{3/2} (\epsilon_{max}/eZ\Delta V)^3, \quad (7)$$

where the dimensionless parameter, $\epsilon_{max}/eZ\Delta V$, can be computed by employing Eqs. (4) and (5) once $\dot{m}$ is specified. The limit of large suppression corresponds to $\kappa \gg 1$, whereas $\kappa \ll 1$ corresponds to small curvature losses. To a good approximation then the luminosity associated with curvature emission is given by $L_\gamma \simeq \kappa L_{CR}$. The curvature spectrum will peak at an energy [6]

$$\epsilon_\gamma \sim 60 (Z/\mu)^3 B_4^3 = 3 \times 10^6 (Z/\mu)^3 \dot{m}^{3/2} \text{ GeV}. \quad (8)$$

We now use the results derived above to estimate the luminosity and spectral peak energy of emitted CRs and curvature photons, for different accretion rates corresponding to different models of Sgr A*. Consider first the possibility of standard accretion with a very low rate. Adopting $\dot{m} = 10^{-7}$ (see above), Eq. (5) yields $\eta \simeq 51$ for protons and $\eta \simeq 47$ for iron. Substituting the latter result into Eq. (4), one finds $\epsilon_{max} \simeq 1.5 \times 10^{16}$ eV for protons and $\epsilon_{max} \simeq 4 \times 10^{17}$ eV for iron. The spectrum of curvature photons should peak at around 100 keV if the accelerated particles are predominantly protons and 10 keV if iron. From Eq. (6) we obtain a CR power of $L_{CR} \simeq 10^{37} \alpha_{CR}$ erg s^{-1}, and from Eq. (7) we obtain a radiative efficiency of $\kappa \simeq 10^{-5.5}$ for both protons and iron and a corresponding gamma-ray luminosity of $L_\gamma \simeq 3 \times 10^{31} \alpha_{CR}$ erg s^{-1}. We therefore conclude that for such a low accretion rate the fluxes of CRs and curvature photons produced by the dynamo mechanism are completely negligible.

We consider next the situation whereby the radio through X-ray spectrum of Sgr A* is produced by an ADAF. Adopting the accretion rate obtained from the standard ADAF model [11], viz., $\dot{m} \simeq 10^{-3}$, and repeating the above calculations we find: $\epsilon_{max} \simeq 10^{18}$ eV for protons and $\epsilon_{max} \simeq 2.5 \times 10^{19}$ eV for iron, a CR power of $L_{CR} \simeq 10^{41} \alpha_{CR}$ erg s^{-1}, a radiative efficiency of $\kappa \simeq 1$ for both protons and iron with a corresponding gamma-ray luminosity $L_\gamma \simeq L_{CR}$, and peak energy for the curvature spectrum of approximately 100 or 10 GeV, depending on whether the accelerated particles are, respectively, protons or iron. We stress that the estimate of the peak energy is highly uncertain because of the strong dependence of ϵ_γ on the strength of the magnetic field (see Eq. (8)). Taking for illustration $\alpha_{CR} = 10^{-3}$, which is roughly the value inferred for the dormant AGNs [5,6], yields $L_{CR} \sim L_\gamma \sim 10^{38}$ erg s^{-1}. The corresponding gamma-ray flux at Earth ($S_\gamma \sim 10^{-8}$ erg cm^{-2} s^{-1}) is several orders of magnitude above the threshold sensitivity anticipated for the HESS [18] and CANGAROO [19] imaging atmospheric Cerenkov telescopes in the southern hemisphere. The photon detections to be obtained with GLAST during a normal one year scan mode are expected to be on the order of a thousand counts or more in this case (Thompson 2000, personal communication).

In addition to the energy losses corresponding to curvature radiation we must also address the possible impact of inelastic pair and pion producing collisions with the environmental electromagnetic radiation near the hole (see Ref. [7]). We estimate that, during the acceleration of a proton to 10^{18} eV by the putative dynamo associated with Sgr A*, there should be negligible drag arising from inelastic pair producing collisions with ambient photons. In particular, since the Lorentz gamma factor is never larger than 10^9 during the acceleration process, only submillimeter (wavelength < 1.2 mm) ambient photons are involved in electron–positron pair production. From the estimated SED of Sgr A* [14,20] we conclude that the corresponding number density of suitable submillimeter photons implies a radiation length about two orders of magnitude larger than the intrinsic size of the radio source [21]. Finally, it is important to note that collisions involving pion generation are of substantially higher inelasticity than those involving pair production [22] and thereby potentially much more catastrophic for the putative dynamo action. However, for inelastic collisions with photo-pion production, only those ambient photons of wavelength shorter than 8 μm are involved; the associated collision mean free path in this instance is then estimated to be even larger than the radiation length characterizing pair production.

3. Discussion

In this paper we have considered the application of a compact black hole dynamo mechanism to CR production by Sgr A*. We have argued that if the rate at which matter is accreted by the black hole is on the order of that estimated on the basis of observations of stellar winds near Sgr A*, then protons of maximum energy $\sim 10^{18}$ eV and total power $\sim 10^{38}$ erg s^{-1} (assuming CR production efficiency of 10^{-3}) can be produced by the dynamo mechanism, provided the black hole angular momentum is near its critical value, and assuming equipartition between the magnetic field threading the horizon and inflowing matter. An associated gamma-ray emission arising from curvature acceleration, with a luminosity comparable to the total CR power released, and with a spectrum that peaks sharply at around 100 GeV is predicted under these conditions, and motivates observations with future missions. Positive detection of curvature photons will have important implications for the process of accretion into the black hole.

Whether the above scenario can explain the excess CR flux reported by the AGASA group recently, even in the case of large accretion rate, remains to be checked; at these energies propagation effects appear to be quite sensitive to the Galactic magnetic field model adopted [3] and should be accounted for properly. The energy flux of the apparent point source offset from the galactic center observed with SUGAR is 3×10^{-11} erg s^{-1} cm^{-2} [2]. Assuming its distance from Earth to be comparable to that of Sgr A*, yields a luminosity of $\sim 2 \times 10^{35}$ erg s^{-1} cm^{-2}. If the SUGAR source is associated with energetic neutrons produced in a target there by the conversion of UHECR protons (or Fe nuclei) originating from Sgr A*, then given the error circle of SUGAR, it implies that the target size should lie in the range between 30 and 300 pc.

Finally, it is interesting to note that the galactic center region is in fact a known gamma-ray source [23], observed over the band 30 MeV to 10 GeV with the EGRET instrument on the Compton GRO to exhibit a hard power law spectrum that steepens above 2 GeV and where the inferred energy flux within the total measured band is 3×10^{-9} erg s^{-1} cm^{-2}; however, the emission volume is likely extended, and the portion arising from a possibly major point source is still uncertain (an issue that should be much better addressed with the improved angular resolution to be provided by GLAST). If we naively associate the break with the peak energy of curvature photons, we obtain from Eq. (8) $\dot{m} \simeq 10^{-4.5}$. From Eqs. (6) and (7) we obtain a luminosity of $L_\gamma \sim 10^{38}\alpha_{CR}$ erg s^{-1}. Assuming that about half the flux is emitted by the point source [23], we obtain a CR production efficiency of $\alpha_{CR} < 0.1$, which seems rather high compared with the efficiency inferred for the dormant AGNs. However, since $\epsilon_\gamma \propto B^3$, as seen from Eq. (8), even relatively small deviations from equipartition would lead to considerably lower peak energy and, consequently, higher values of $\dot{m}$ and lower values of α_{CR}. Alternatively, the potential curvature radiation from Sgr A* might well be a separate gamma ray component from that detectable with EGRET (e.g., at a much higher energy, such as characteristic of the case illustrated here).

Acknowledgements

We thank Michael Loewenstein, Gustavo Medina–Tanko and David Thompson for enlightening discussions.

References

[1] N. Hayashida et al., Astropart. Phys. 10 (1999) 303.
[2] J.A. Bellido, R.W. Clay, B.R. Dawson, M. Johnston-Hollitt, Astropart. Phys. 15 (2001) 167.

[3] R.W. Clay, Astropart. Phys., submitted for publication.
[4] R.W. Clay, B.R. Dawson, J. Bowen, M. Debes, Astropart. Phys. 12 (2000) 249.
[5] E. Boldt, P. Ghosh, Mon. Not. Roy. Ast. Soc. 307 (1999) 491.
[6] A. Levinson, Phys. Rev. Lett. 85 (2000) 912.
[7] E. Boldt, M. Loewenstein, Mon. Not. Roy. Ast. Soc. 316 (2000) L29.
[8] B. Punsly, F.V. Coroniti, Astrophys. J. 350 (1990) 518.
[9] J.F. Hawley, J.H. Krolik, Astrophys. J. 548 (2001) 348.
[10] A. Eckart, R. Genzel, Mon. Not. Roy. Ast. Soc. 284 (1997) 576.
[11] R. Narayan, R. Mahadevan, L. Grindlay, Astrophys. J. 492 (1998) 554.
[12] F. Melia, Astrophys. J. 387 (1992) L25.
[13] R. Genzel, D. Hollenbach, C.H. Townes, Rep. Prog. Phys. 57 (1994) 417.
[14] H. Falcke et al., Astrophys. J. 499 (1998) 731.
[15] E. Quataert, R. Narayan, Astrophys. J. 520 (1999) 298.
[16] R.D. Blandford, M.C. Begelman, Mon. Not. Roy. Ast. Soc. 303 (1999) L1.
[17] R. Narayan, I. Yi, Astrophys. J. 444 (1995) 231.
[18] A. Kohnle, Proceedings of the 26th International Cosmic Ray Conference, Salt Lake City, vol. 5, 1999, p. 280.
[19] T. Tanimori et al., 1999, Proceedings of 26th International Cosmic Ray Conference, Salt Lake City, vol. 5, p. 203.
[20] T. Beckert, W.J. Duschl, in: H. Falcke et al., (Eds.), The Central Parsec of the Galaxy, ASP Conf. Ser. vol. 186, 1999, p.138.
[21] K.Y. Lo, Z.-Q. Shen, J.-H. Zhao, P.T.P. Ho, in: H. Falcke, et al. (Eds.), The Central Parsec of the Galaxy, ASP Conf. Ser. 186, 1999, p. 72.
[22] F. Stecker, Phys. Rev. Lett. 21 (1968) 1016.
[23] H.A. Meyer-Hasselwander et al., Astron. Astrophys. 335 (1998) 161.