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HIGH-ENERGY RADIATION FROM A MODEL OF QUASARS, ACTIVE GALACTIC NUCLEI, AND THE GALACTIC CENTER WITH MAGNETIC MONOPOLES

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ABSTRACT

The fact that magnetic monopoles may catalyze nucleon decay (the Rubakov-Callan [RC] effect) as predicated by the grand unified theory of particle physics is invoked as the energy source of quasars and active galactic nuclei. Recent study of this model revealed that the radius of the supermassive object (SMO) located at the Galactic center is much larger than its Schwarzschild radius. We propose that this SMOs could be the source of high-energy gamma-ray radiation, although the emitted radiation may be mainly concentrated in the infrared.

The surface temperature of the SMO at the Galactic center is taken as 121 K, inferred from the observed maximum of the flux spectrum of Sgr A* at the near infrared (1×10^{13} Hz); the radius of the SMO is about 8.1×10^{15} cm or $1.1 \times 10^4 R_S$ (R_S is the Schwarzschild radius). The mass of the SMO is derived from the observed total luminosity of Sgr A* (1×10^{37} ergs s^{-1}) as $2.5 \times 10^6\ M_\odot$. Strong gamma-ray radiation with energy higher than 0.5 MeV may be emitted from the SMO. The flux of positrons emitted from the SMO is estimated to be $6.5 \times 10^{42} e^+$ s^{-1}. The content parameter of magnetic monopoles $\xi \equiv [(N_m/N_B)/1.9 \times 10^{-25}](\langle\sigma\beta\rangle/10^{-27})$ also may be deduced from observations to be 230. Taking the cross section of the RC effect as 1×10^{-27} cm^2, the strength of the radial magnetic field at the surface of the SMO is estimated to be 20–100 G. Our model also can predict the production of extreme ultra–high-energy cosmic rays.

Subject headings: cosmic rays — galaxies: active — galaxies: magnetic fields — gamma rays: bursts — quasars: general

1. INTRODUCTION

The study of supermassive stellar objects (SMOs) has attracted considerable interest of both theoretical physicists and observational astronomers ever since the discovery of quasars. It is now generally believed by most astronomers that bright quasars observed at large redshift (for example, $z > 1$ or even $z > 5.0$) are supermassive black holes ($M > 10^{10}\ M_\odot$) formed in the primordial universe. The spectacularly huge luminosity is supplied by the accretion of matter outside these black holes. As a result, the mass of nearby galactic nuclei and quasars must be greater than that of the remote quasars with larger redshift. This is because the mass of the black holes must continuously increase due to accretion. Indeed, this is the dilemma of the black hole model of quasars and active galactic nuclei (AGNs).

On the other hand, the merger of two galactic nuclei may also form a quasar or an AGN. However, this proposal is relatively new, and it is doubtful whether this new theory can account for most of the observational data. Therefore, as an alternative, a new model for the evolution of quasars and AGNs was proposed by us (Peng & Chou 1997). The most important novel ingredient in our new evolutionary model for quasars and AGNs is the key role played by magnetic monopoles. It is well known that magnetic monopoles of the 't Hooft-Polyakov type ($m_m \approx 10^{16} m_B$; $g_m = 3hc/4\pi e = 9.88 \times 10^{-8}$ G, where g_m is the magnetic charge of a stable colorless monopole and m_m and m_B are the masses of monopole and baryon, respectively) may catalyze nucleon decay as suggested by the grand unified theory of particle physics (the Rubakov-Callan [RC] effect):

$$\begin{aligned} pM &\rightarrow Me^+\pi^0 + \text{debris (85\%)} \\ &\rightarrow Me^+\mu^+\mu^- + \text{debris (15\%)}. \end{aligned} \tag{1}$$

It was pointed out that both the mass and luminosity of quasars and AGNs would gradually decrease in time because their constituent baryons are kept decaying and are transformed into radiation. By invoking the RC effect as the energy source, it was shown that these SMOs with enough magnetic monopoles have neither horizon nor central singularity, although their radii are smaller than the Schwarzschild radius (Peng 1989; Peng, Li, & Wang 1985; Peng, Wang, & Li 1986).

In this Letter, we focus on the emission of high-energy radiation resulting from our model for SMOs and specialize our results to the Galactic center. Some important observations that are relevant to our discussions on the high-energy radiation originating from the Galactic center will be briefly presented in § 2. Important features and predictions of our model for the Galactic center are elaborated in § 3. The production of extreme ultra–high-energy cosmic rays is briefly depicted in § 4.

2. SOME INFORMATION ON THE GALACTIC CENTER FROM OBSERVATIONS

We summarize the information on the Galactic center taken from observations as follows:

1. It seems that most astronomers believe in the existence of a supermassive central black hole in Sgr A* although its Schwarzschild radius is $R_S \sim 7.4 \times 10^{11}$ cm. Dynamical measurements indicate that a dark mass of $(2.5 \pm 0.4) \times 10^6\ M_\odot$ exists within the central region about 0.1 pc from the Galactic center (Haller et al. 1996; Eckart & Genzel 1997), and this is taken as the mass of the SMO at the Galactic center.

2. The total luminosity of Sgr A* as derived from radio to gamma-ray observations is $\lesssim 10^{37}$ ergs s^{-1}. The extremely low

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luminosity has been used to argue against the common belief that Sgr A* is an accreting black hole (Gordwurm et al. 1994). We will take the bolometric (i.e., the total thermal) luminosity L_B for the SMO to be 10^{37} ergs s^{-1}, which is a part of the total luminosity mainly produced by the RC effect:

$$L_B = \eta L_{\rm tot}. \tag{2}$$

In other words, we assume that a factor η of the total energy produced by the RC effect as represented by equation (1) is transformed into thermal radiation and that the remainder of the total energy release is converted into various nonthermal high-energy radiation through a series of cascades. Using the observational results from gamma-ray radiation (discussed in point 4), the factor η may be estimated to be ∼0.05–0.2.

3. The spectrum of Sgr A* as derived from radio to near-infrared (NIR) has been fairly constant ever since the discovery of the source. The observation has been carried out from 400 MHz (Davis, Walsh, & Booth 1976) to $\sim 10^{14}$ Hz. According to a compilation of the radio to NIR observations (Narayan et al. 1998), the maximum of νL_ν is at $\nu_{\rm max} = 1.0 \times 10^{13}$ (see Fig. 1 of Narayan et al.); thus, the surface temperature of the SMO may be estimated by the Planck blackbody radiation law:

$$T \approx \frac{h\nu_{\rm max}}{4k} \approx 121 \text{ K}. \tag{3}$$

The radius of the SMO can be estimated according to the formula $L_B = 4\pi R^2 \sigma T^4$. Using the estimated values for the thermal luminosity and surface temperature given above, the radius may be calculated to be $R \approx 8.1 \times 10^{15}$ cm. It is convenient at this point to introduce a dimensionless radius for the SMO by $y = R/R_{\rm S}$ ($R_{\rm S} = 2GM/c^2$ is the Schwarzschild radius); here $y = 1.1 \times 10^4$.

4. The relevant observational data on the dense positron-electron annihilation line at our Galactic center, which was detected early by balloons (Johnson & Haymes 1973; Haymes et al. 1975) and by satellites (Riegler et al. 1981) and was further measured by the Transient Gamma-Ray Spectrometer (Harris et al. 1998), may be briefly summarized as follows: the energy of the spectral line is $0.51098(\pm 0.10 \pm 0.04) \times 10^{-3}$ MeV with very small gravitational redshift ($z \lesssim 7 \times 10^{-4}$); the 0.511 MeV line flux is $\sim(1.07 \pm 0.05) \times 10^{-3}$ photons cm^{-2} s^{-1}. Taking the distance of the Galactic center to the Sun as 8.0 kpc, the intensity of the spectral line is $\sim 6.7 \times 10^{36}$ ergs s^{-1}, corresponding to annihilation of $\sim 8.2 \times 10^{42} e^+$ s^{-1}; the width of the line is very small, FWMH $= 1.81 \pm 0.54 \pm 0.14$ keV. A strong continuum radiation with energy higher than 0.511 MeV is also detected. For example (Lingenfelter & Ramaty 1989), the ratio of the luminosity for the positron annihilation line to that of the continuum with energy greater than 0.511 MeV is $L(e^+)/L(>0.511) \approx 0.03$, i.e., $L(>0.511) \sim (2.0 \pm 0.4) \times 10^{38}$ ergs s^{-1}. At much higher energies, in the range from 100 MeV to 1 GeV, gamma-ray continuum emission has also been observed (Swanenburg et al. 1981) from the region within 300 pc of the Galactic center at a luminosity of $\sim 10^{37}$ ergs s^{-1}.

3. PREDICTION OF OUR MODEL OF THE GALACTIC CENTER

3.1. *Positrons Emitted from the SMO in our Model*

We now calculate the positron production rate from our theoretical model of an SMO with magnetic monopoles. The reaction rate of the RC effect is

$$r_{\rm RC} = N_B N_m \langle \sigma V \rangle = 2.07 \times 10^6 \rho^2 \xi, \tag{4}$$

where ρ represents the mass density inside the SMO and ξ is a content parameter of magnetic monopoles:

$$\xi \equiv [(N_m/N_B)/1.9 \times 10^{-25}](\langle \sigma\beta \rangle/10^{-27}), \tag{5}$$

where $\beta = V/c$, N_B, and N_m denote the number density of the baryons and the monopoles, respectively. The rate of the total energy release of the object is then

$$L_{\rm tot} = 4\pi \int_0^R r_{\rm RC} R^2\, dR = A_L \Psi \xi m^{-1} y^{-3}, \tag{6}$$

where $A_L = 4.4 \times 10^{46}$ ergs s^{-1}, $m = M/(2.5 \times 10^6\, M_\odot)$, M is the mass of the object, and Ψ is defined as

$$\Psi = \frac{\int_\nu \rho^2\, dV}{(\bar{\rho})^2}. \tag{7}$$

To evaluate Ψ we will consider two different density profiles. For model A, the density distribution in equation (7) is given by $\rho(r) \propto r^{-1}$; we then have $\Psi = 1.3$. For model B, the density profile is assumed to be $\rho(r) \propto (r^2 + \epsilon^2)^{-1}$; then

$$\Psi = \frac{\pi}{4\epsilon} - \frac{1}{6} \approx \frac{\pi}{4\epsilon} \gg 1 \text{ if } \epsilon \ll 1.$$

We may also estimate the parameter ξ for the content of the magnetic monopoles inside the SMO. Combining equations (2) and (6), and using the bolometric luminosity L_B together with the radius R or its dimensionless form y inferred from observations (see § 2), the result may be cast in the simple form

$$\eta\xi \approx 230. \tag{8}$$

The positron emission rate from the SMO due to the RC effect and the subsequent cascade process is thus

$$S_{e^+} \approx \frac{4\pi}{3} R^3 \bar{r}_{\rm RC} \bar{\Delta} \approx A_e \left(\frac{\bar{\Delta}}{300}\right) \Psi \xi m^{-1} y^{-3}, \tag{9}$$

where $A_e = 7.7 \times 10^{51} e^+$ s^{-1}. Combining equation (8) with equation (9) and noting that $y = 1.1 \times 10^4$, we obtain $S_{e^+} \approx 1.3 \times 10^{42} \eta^{-1} e^+ s^{-1}$. The positron production rate is therefore $\sim 6.5 \times 10^{42} (\eta/0.2)^{-1} e^+$ s^{-1} ($\eta \sim 0.05$–0.2).

3.2. *High-Energy Gamma-Ray Radiation*

Besides the gamma rays of the positron annihilation line, the radiation with energy higher then 0.5 MeV is also produced from the SMO as a result of the RC effect and through the cascade process for multiplication. However, the energy of the gamma-ray photons is decreased during the cascade. We note that the total integrated energy of these high-energy radiations would be much greater than both the energy of positron annihilation line and the bolometric luminosity. This prediction is qualitatively consistent with the observation (see § 2).

3.3. *Radial Magnetic Field*

The radial magnetic field from the surface of the SMO is $H(R) = Q_m/R^2$, where Q_m is the total magnetic charge of the stellar object,

$$Q_m = N_m q_m = \zeta N_B q_m = \zeta_n q_m M(\zeta). \qquad (10)$$

Thus,

$$H(R) = \frac{c^4 q_m \zeta_n}{4Gm_B}(2.5 \times 10^6 M)^{-1}\left(\frac{\langle\sigma\beta\rangle}{10^{-27}\ \mathrm{cm}^2}\right)^{-1}\xi m^{-1}y^{-2}$$
$$= 1.1 \times 10^8 \left(\frac{\langle\sigma\beta\rangle}{10^{-27}\ \mathrm{cm}^2}\right)^{-1}\xi m^{-1}y^{-2}. \qquad (11)$$

Substituting the value of y, and setting $m = 1$, we then have $H(R) = 190(\langle\sigma\beta\rangle/10^{-27})^{-1}(\eta\Psi)^{-1}$. We may take $(\eta\Psi)^{-1} \sim 0.5$–0.1; then the strength of the radial magnetic field is $H(R) \sim (20$–$100)$ G. We note that the presence of the radial magnetic field is one of the criterions of the important predictions of our model, and it also may be checked by radio observations in the near future.

4. THE PRODUCTION OF EXTREME ULTRA–HIGH-ENERGY COSMIC RAYS

The possible existence of supermassive and compact stellar objects with enough saturated magnetic monopoles has already been proposed by one of us (Peng 1989) as a possible model for quasars and AGNs. These compact stellar objects may collapse in such a way that their radii can be even smaller than the Schwarzschild radius R_S, and yet they have neither horizon nor central singularity because nucleon decay catalyzed by magnetic monopoles in the interiors of such compact and massive objects can prevent their central densities from becoming infinite. These exotic stellar objects can rotate so fast that their spinning angular momentum may even approach the extreme value of angular momentum of the Kerr black hole.

To proceed, we will assume that the surface spinning speed V_p at the equator of such highly collapsed SMOs may reach a significant fraction of the speed of light, so that their rotation is slower than the extreme rotation limit of a Kerr black hole. In the inertia frames that corotate with the spinning body, these exotic objects possess strong radial magnetic fields with field strength 20–100 G. It is expected that in the rest frame of a distant observer, there must be a strong electric field. For instance, the electric field $E_z(r)$, at a distance r from the center but perpendicular to the extended equatorial plane of the stellar object, may be readily obtained by a simple Lorentz transformation to yield

$$E_z(r) = \frac{V_p/c}{\sqrt{1-(V_p/c)^2}} H(R)\left(\frac{R}{r}\right)^2. \qquad (12)$$

In other words, the direction of the electric field is parallel to the spinning axis of the compact stellar object.

It is interesting to note that the electric field $E_z(r)$ as given by equation (12) can be felt at a considerably large radial distance r even though the field has an inverse square decrease. For highly collapsed compact and supermassive stars (for example, $M \sim 10^8\ M_\odot$, $R \sim R_S \sim 3 \times 10^{13}$ cm), $y \sim 1$, $\xi \sim 1$–200 or even more. Then from equation (11), the radial magnetic field at the surface of such exotic stellar objects may reach 10^6–10^8 G, and the electric field can still be significant even at $r \sim 100R \sim 10^{-3}$ pc. The energetic particles (e^+, $\mu^\pm$, π^0) produced in the stellar interior via the RC effect may possess an initial energy of several hundred MeV.

A variety of energetic particles may be generated through the processes $\pi^0 \rightarrow 2\gamma$, $\pi^0 \rightarrow 3\gamma$, and pair annihilation of positrons with background electrons into high-energy photons. These photons may transform into high-energy electrons via Compton scattering or $\gamma + \gamma \rightarrow e^+ + e^-$. During the long flight of these energetic particles, they are continuously accelerated by the strong electric field to extreme ultra–high energy. The governing equation for the extreme relativistic charged particles may be approximately written as

$$\frac{d}{dt}\gamma = \frac{q_e E_z}{m_0 c}. \qquad (13)$$

Moreover, equation (13) may be slightly modified to a more useful form by setting $dr \sim bc\ dt$, where the factor b takes into account the effect of nonradial motion. Let $u = r/R$; equation (13) may then be recast in the form

$$\frac{d\gamma}{du} \approx \frac{\Gamma}{u^2}, \quad \Gamma = \frac{1}{b}\frac{q_e R}{m_0 c^2}\frac{V_p}{c}\left[1-\left(\frac{V_p}{c}\right)^2\right]^{-1/2} H(R). \qquad (14)$$

From equation (14) we may easily estimate the energy of those charged particles that are accelerated by the strong stellar electric field from the stellar surface to infinity. The simple estimate yields

$$\gamma = \gamma_0 + \Gamma \approx \Gamma \ (\gamma_0 \ll \Gamma). \qquad (15)$$

For instance, for electrons, even if $V_p/c \sim 0.1$, $R \sim 3 \times 10^{13}$ cm, $M \sim 10^8\ M_\odot$, and $H(R) \geq 10^6$ G, then $\Gamma \geq 10^{14}$. In other words, the energy of the electrons emitted from such exotic stellar objects with magnetic monopoles may reach 10^{21} eV or greater ($\gamma \sim 2 \times 10^{15}$). Thus, our model with magnetic monopoles can provide naturally an effective mechanism for producing extreme ultra–high-energy cosmic-ray particles. This novel mechanism can easily explain the appearance of a large amount of ultra–high-energy electrons in the vicinity of most of the AGN.

In addition, the annihilation of opposite magnetic monopoles may lead a release of even much greater energy: 10^{25} eV. It is anticipated that the collision of two AGNs, each with mass of $\sim 10^8\ M_\odot$ and with the Newtonian saturation of magnetic monopoles but with opposite magnetic charge could generate 10^{53} ergs of energy. Consequently, it might also be considered as a possible alternative origin of a gamma-ray burst. Our mechanism is very efficient in that it can convert almost all its energy into high-energy gamma rays and ultra–high-energy cosmic rays without the problem of baryon contamination as in the standard theory of gamma-ray bursts. The spectrum index in our model is further investigated via Monte Carlo simulation, and the result will be reported in future publications.

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