A MODEL OF QUASARS AND AGNS WITH MAGNETIC MONOPOLES

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Abstract. An evolutionary model of quasars and AGNs with magnetic monopoles is proposed. Their energy source is due to nucleon decay induced by the monopoles. Both the mass and the luminosity of quasars and AGNs will gradually decrease in time because their constituent baryons are kept decaying and are transformed into radiation. The physical significance and theoretical predictions of our evolutionary model are stressed.

1. Introduction

Bright quasars observed at large red-shift (for example, $z > 1$, even $z > 4.0$) are generally believed by most astronomers to be supermassive black holes ($M > 10^{10} M_{\odot}$) formed in the primordial universe. Their huge luminosity is supplied by the accretion of matter outside these black holes. We may naturally come to the conclusion that the mass of nearby galactic nuclei and quasars must be greater than that of the remote quasars with larger red-shift, because the mass of the black holes must continuously increase due to accretion. However, no convincing observational evidence supports this conclusion. Indeed, this is the dilemma of the black hole model of quasars and AGNs. On the other hand, a quasar or an AGN may also be formed by the merger of two galactic nuclei. This proposal is relatively new, and there are many different aspects of the observational results about quasars and AGNs which still have to be explained and it is doubtful whether this new theory can account for most of the observational data. Therefore, as an alternative, we would like to propose a new model for the evolution of quasars and AGNs.

The most important novel ingredient in our new evolutionary model for quasars and AGNs is the role played by magnetic monopoles. It is well known that magnetic monopoles of the ‘t Hooft-Polyakov type may catalyze nucleon decay as suggested by the grand unified theory of particle physics and this is known in the literature as the Rubakov-Callen effect (henceforth referred to as the RC effect). By invoking the RC effect as the energy source, a model of active galactic nuclei with the Newtonian saturation of magnetic monopoles has already been proposed earlier by one of us (Peng *et al.*, 1985, 1986, 1989). It was shown there that these super-

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massive stellar objects with enough magnetic monopoles have neither horizon nor central singularity, although their radii are smaller than the Schwarzschild radius. In Section 2 of this paper we briefly describe the general background of our model and discuss the number of magnetic monopoles contained in the various possible types of celestial bodies. The scheme of our galactic nucleus model with magnetic monopoles is elaborated in Section 3. In Section 4 we present an evolutionary model for supermassive stellar objects such as quasars and AGNs and briefly delineate their characteristic features. Finally, in Section 5 we stress the distinctive implication of our evolutionary model and compare it with the prediction of other theories of quasars and AGNs.

2. Background

A tiny amount of magnetic monopoles may be produced by the violent oscillation and thermal fluctuation of the Higgs field during the phase transition of the initial universe which is very hot ($kT > 10^{15}$ Gev) and in a highly chaotic state (Guth, 1982). For a superheavy magnetic monopole of the 't Hooft-Polyakov type, we have $m_m \approx 10^{16} m_B$; $g_m = 3hc/4\pi e = 9.88 \times 10^{-8}$ Gauss ($= 3 \times (g_m)_{Dirac}$), where g_m is the magnetic charge of a stable colorless monopole, m_m, m_B are the masses of monopole and baryon respectively. The Rubakov-Callan (RC) effect (1981–1983) means that a magnetic monopole may catalyze nucleon decay:

$$\begin{aligned} pM &\to Me^+\pi^0 \quad (85\%) \\ &\to Me^+\mu^+\mu^- (15\%) \end{aligned} \tag{1}$$

its cross-section is $\sigma \sim 10^{-25} - 10^{-26}$ cm^2 (Rubakov, 1983; Callan, 1982) or $\sigma \sim 10^{-36}$ cm^2 (Wilczek, 1982).

We now consider the saturation and critical number of monopoles contained in celestial objects. The upper limit for the number of monopoles in the universe has been suggested by Parker (1970) and Lazarides (1981) to be $\zeta (\equiv N_m/N_B) \leq \zeta^0 \leq 10^{-20\pm1}$, but this is still much higher than the Newtonian saturation content of monopoles in stellar object as presented earlier (Peng *et al.*, 1985):

$$\zeta \leq \zeta_n = G m_B m_m / g_m^2 \approx 1.9 \times 10^{-25} (m_m / 10^{16} m_B). \tag{2}$$

Moreover, using the theory of general relativity Peng (1989) calculated the saturation content of monopoles in a non-rotating stellar object:

$$\begin{aligned} \zeta_s &= \zeta_n (1 - R_g/R)^{-1/2} \quad && (R \gg R_g) \\ \zeta_s &= \zeta_g \sqrt{R/R_g} && (R \sim R_g \text{ or } R \leq R_g) \end{aligned} \tag{3}$$

where $\zeta_g = 214\zeta_n$, and $R_g = 2GM/c^2$ is the Schwarzschild radius. Furthermore, using the Kerr-Newman-Kasaya metric, Peng has also obtained the critical content of monopoles for a rotating stellar object (Peng, 1989):

$$\zeta_c = \zeta_{c0}(1 - 4a^2/R_g^2)^{1/2}, \tag{4}$$

where $\zeta_{c0} \equiv \sqrt{Gm_B/g_m} = 4.365 \times 10^{-21}$, and $a \equiv J/Mc$ is the specific angular momentum. The horizon of the dense supermassive stellar object with magnetic monopole is given by

$$r^h = \frac{1}{2}R_g\{1 + [1 - 4(a^2 + \kappa Q^2)/R_g^2]^{1/2}\}, \tag{5}$$

where $\kappa \equiv G/c^4$, $Q^2 = Q_e^2 + Q_m^2$, Q_e, Q_m is the total electric and magnetic charge of the object respectively. We note that the horizon of a collapsed supermassive stellar object will disappear when its magnetic monopole content is greater than the critical value ζ_c.

We will now consider the number of monopoles in stellar objects. We note that the number of monopoles possibly contained in a stellar object is closely related to the initial physical condition in the primary cloud from which the object was born. For example, in the interior of a protostar (the number density of hydrogen atoms $\sim (10^2 - 10^4)$ cm^{-3} and temperature $\leq 100°$ K), the interaction of monopoles with neutral atoms is insignificant, and very few monopoles will be drawn by the neutral matter during the collapse of a primary cloud (molecular or neutral hydrogen). On the other hand, the interaction of monopoles with plasma is so strong (Li, 1986) that many monopoles will be drawn into the quasars and AGNs during their formation. The number of monopoles contained in stellar objects has been estimated by Peng *et al.* (1985) with the following result:

(1) The monopoles in both normal stars and planets are so few as to be undetectable (the probability to detect them is less than 10^{-7} years). The monopoles contained in stellar objects are mainly due to capture $\zeta/\zeta_n \leq 10^{-12}$.

(2) The number of monopoles contained in neutron stars and white dwarfs is mainly due to capture. The number of monopoles in such compact stellar objects is much higher than that contained in normal stars:

$$\frac{\zeta}{\zeta_n} \leq (10^{-2} \sim 10^{-3})\frac{R}{R_g}\frac{M}{M.}\left(\frac{\langle\sigma\beta\rangle}{10^{-27}\ \mathrm{cm}^2}\right)^{-1}\frac{\tau}{10^{10}\ \mathrm{yr}}, \tag{6}$$

where $\langle\sigma\beta\rangle$ is the average rate of the Rubakov-Callan effect, τ is the age of the evolved dense stellar object.

(3) The monopoles in quasars and AGNs are primarily produced during the primordial epoch of galaxy formation, while matter was still in a dense plasma state

at high temperature. Due to the strong monopole-plasma interaction, the number of monopoles in quasars and AGNs may be much higher than that contained in stars, planets, neutron stars and white dwarfs so that:

$$\frac{\zeta}{\zeta_0} \sim 10^{-3}(V_m/10^{-4}c)^{-3/2}M_{12}^{1/2},$$

where $M_{12} = M/10^{12}M.$, V_m is the average velocity of monopoles, $V_m < 10^{-4}c$ (Lazarides *et al.*, 1981).

3. Our Model of Galactic Nuclei with Monopoles

By invoking the RC effect as their energy source, a model of galactic nuclei with the Newtonian saturation of magnetic monopoles was suggested (Peng, Wang and Li, 1986). For example, a model of galactic nuclei may be obtained by taking its mass $M \approx 1 \times 10^7 M.$ and its luminosity $L \approx 3 \times 10^7 L.$, which is rather dense, if we take $\xi \geq 10^{-7}$ see equation (8). A specific model is defined by $\xi = 1$, then $R = 625R_g \approx 1.8 \times 10^{15}$ cm, and the surface temperature is about 3000° K. The strength of the radial magnetic field is then roughly

$$H = \frac{N_m q_m}{R^2} = \frac{M\zeta_n q_m}{m_B R^2} \approx 70(\langle\sigma\beta\rangle/10^{-27}\ \mathrm{cm}^2)^{-1}\ \text{gauss}. \tag{7}$$

We would like to emphasize that an accretion disk around the central compact object may still exist and the properties of our model are similar to the usual (black hole) model. The difference is the fact that the huge stellar object in our model is not a black hole and the main energy source is due to the induced nucleon decay catalyzed by magnetic monopoles.

The characteristics of our model may therefore be outlined as follows:

(1) Our model of supermassive stellar objects for quasars and AGNs with Newtonian saturation of monopoles is a strong infrared source with a black body spectrum.

(2) The radial magnetic field of these objects originates from the monopoles inside and may be checked by observation.

(3) Furthermore, our model predicts the 0.511 Mev γ ray line radiation which is produced by the pair annihilation with a very strong flux ($\sim 10^{43} e^+$/sec), and some of the high energy γ-rays originate directly from the center of our Galaxy (Wang and Peng, 1986; Wang *et al.*, 1986). These γ rays were detected 15 years ago. Taking the RC effect into account, it can be shown by general relativity that a supermassive object may not have a black hole ($R/R_g > 1$), provided that

$$\xi \equiv (\zeta/\zeta_n)(\langle\sigma\beta\rangle/10^{-27}\ \mathrm{cm}^2) > 10^{-7} \tag{8}$$

(Peng *et al.*, 1986). The ratio of the number of monopoles is to that of baryons will increase continuously due to nucleons decaying (induced by monopoles) and their unceasing conversion into radiation. The mass of these objects will also decrease due to the RC effect, but the number of monopoles remains constant. This is because the superheavy monopoles are deposited and accumulated near the central region of the objects. It is possible that the number of monopoles contained in some or most of the supermassive galactic nuclei and quasars approaches saturation. It can also be seen that a fast rotating collapsed stellar object satisfying the inequality

$$a > (GM^2/c^2)[1 - (\zeta/\zeta_{c0})^2]^{1/2} \tag{9}$$

is not yet a black hole, even if $\sigma \sim 10^{-36}$ cm^2 (Peng, 1989).

Neither horizon nor singularity can exist at its center for this fast rotating collapsed object. This is because the rate of the catalytic reaction of the RC effect increases rapidly towards the center, which is proportional to the square of density. It follows that:

(1) As the energy of the nucleons (including their rest energy) is almost completely transformed into radiation, a strong radiation pressure will be generated and will repulse the matter outwards so that the collapse of the object will stop.

(2) The central gravitational force will immensely decrease due to the decrease of the mass of the object resulting from the RC effect. The more violent the collapse, the faster the process. It will eventually prevent the object from collapsing indefinitely. Thus, as long as the RC effect is valid, there is no singularity at the center of the collapsed supermassive object.

4. An Evolutionary Model of Quasars and AGNs

The luminosity of a galactic nucleus is due primarily to the induced decay of nucleons catalyzed by magnetic monopoles (Peng *et al.*, 1986):

$$L = A_L \xi x M_8, \tag{10}$$

where the constant A_L and the parameters x, M_8 are defined by

$$A_L = 2.1 \times 10^{44} \text{ erg/sec}, \; x = \rho_c/(1.84 gr/\text{cm}^3), \; M_8 = M/10^8 M_{\odot}.$$

The mass of the supermassive stellar object will also decrease due to the conversion of nucleons into radiation

$$-\frac{dM}{dt} = \frac{L}{c^2}. \tag{11}$$

The internal structure of supermassive stellar objects such as quasars and AGNs is by no means clearly understood at present. In particular, how the central density of such supermassive objects changes with mass is not really known. For simplicity, we therefore assume the following power law for the variation of central density with mass

$$\rho_c = \rho_{c,0}(M/M_0)^{\alpha}. \tag{12}$$

We then obtain

$$-\frac{dM}{dt} \propto \frac{\zeta}{\zeta_n} M^{(1+\alpha)}. \tag{13}$$

In order to study the evolution of mass and luminosity of quasars and AGNs, we must consider two different cases:

(1) When the number of magnetic monopoles contained in the supermassive stellar objects is less than the saturation value. In this case, the repulsive Coulomb force arising from monopoles of the same charge is still weaker than the gravitational force experienced by the monopoles, so that the monopoles cannot escape from the interior of these stellar objects. Furthermore, the mass of such monopoles is so huge ($m_m \approx 10^{16} m_B$) that they could not be blown out by stellar wind. Consequently, the number of monopoles is a constant.

(2) When the number of monopoles reaches its saturation value, the situation is different. Baryons are converted into radiation through the RC effect, so that both the number of baryons and the mass of the stellar object gradually decrease. The equilibrium between gravitational force and the coulomb repulsion due to similar monopoles can no longer be maintained and the magnetic force exceeds the gravitational force so that these extra supersaturated monopoles near the surface of the stellar object are repelled from its surface. In this case the number of monopoles in the stellar object gradually decreases. However, the ratio of the number of monopoles to the number of baryons, ζ, now remains at the constant saturation value ζ_s.

The evolutionary scenario for the two cases is different.

[1] $\zeta < \zeta_s$. As previously explained, the number of monopoles is a constant, namely, $N_m = N_{m,0} =$ constant. However, both the number of baryons N_B and the mass M of the stellar object decrease. As a result, the ratio of the number of monopoles to the number of baryons ζ increases. The governing equation for the evolution is depicted by Equation (14).

$$-\frac{d}{dt}(M/M_0) = B(M/M_0)^{\alpha}, \tag{14}$$

$$B = (A_L/10^8 M.c^2) x_0 \xi_0 \tag{15}$$

$$\tau_1 = 1/B \approx 3 \times 10^{10} (x_0 \xi_0)^{-1} \text{ yr.} \tag{16}$$

For detailed scrutiny, it is more convenient to further examine the following two cases:

(a) If $\alpha \neq 1$, then

$$M/M_0 = [1 - (1-\alpha)(t/\tau)]^{1/(1-\alpha)}, \tag{17}$$

$$L \propto M^\alpha;\ L/L_0 = [1 - (1-\alpha)(t/\tau)]^{\alpha/(1-\alpha)}, \tag{18}$$

$$\zeta/\zeta_0 = (M/M_0)^{-1} = [1 - (1-\alpha)(t/\tau)]^{-1/(1-\alpha)}. \tag{19}$$

During the early phase of the universe, $t \ll \tau$ we then have

$$\frac{M}{M_0} \approx 1 - t/\tau,\ \frac{L}{L_0} \approx 1 - \alpha t/\tau,\ \zeta \approx 1 + t/\tau. \tag{20}$$

(b) If $\alpha = 1$, then

$$M = M_0 e^{-t/\tau},\ L = L_0 e^{-t/\tau},\ \zeta = \zeta_0 e^{t/\tau}. \tag{21}$$

Thus both the mass and the luminosity of the supermassive stellar object decrease exponentially with time. However, the number of magnetic monopoles and the ratio of the number of magnetic monopoles to that of baryons ζ increase.

[2] $\zeta \geq \zeta_s$. As explained previously, both the number of monopoles N_m and the number of baryons N_B decrease. However, the ratio of the number of magnetic monopoles to the number of baryons ζ now remains at the constant saturation value ζ_s.

$$\frac{\zeta_s}{\zeta_n} = (1 - R_g/R)^{-1/2} \quad (R \gg R_g) \tag{22}$$

$$\frac{\zeta_s}{\zeta_n} = 214\sqrt{R/R_g} \quad (R \sim R_g \text{ or } R \leq R_g). \tag{23}$$

To examine more closely we note that

(2a) If $\zeta_s \approx$ constant (when $R \gg R_g$)

$$-\frac{d}{dt}(M/M_0) = C(M/M_0)^{1+\alpha}, \tag{24}$$

$$C = (A_L/10^8 M.c^2)x_0(\langle\sigma\beta\rangle/10^{-27}\ \text{cm}^2)(\zeta_s/\zeta_n) \tag{25}$$

$$\tau_2 = C^{-1} \approx 3 \times 10^{10}(x_0)^{-1}(\langle\sigma\beta\rangle/10^{-27}\ \text{cm}^2)^{-1}\ \text{yr}, \tag{26}$$

where we have used $\zeta_s/\zeta_n \sim 1$.

For detailed scrutiny, we further study the two sub-cases:

(i) If $\alpha \neq 0$, then

$$M/M_0 = (1 + \alpha t/\tau)^{-1/\alpha} \tag{27}$$

$$L \propto M^{1+\alpha}, \ L/L_0 = (1 + \alpha t/\tau)^{-(1+\alpha)/\alpha}. \tag{28}$$

(ii) If $\alpha = 0$,

$$M = M_0 e^{-t/\tau}, L = L_0 e^{-t/\tau}. \tag{29}$$

(2b) When the radius of the stellar object is close to or smaller than the Schwarzschild radius, the saturation value for the number of monopoles also decreases with its radius. The evolutionary scenario is delineated by Equation (30).

$$R/R_g = (M/M_0)^{2\alpha_1}, \text{ then } \frac{\zeta_s}{\zeta_n} = 214 \left(\frac{M}{M_0}\right)^{\alpha_1}.$$

$$-\frac{d}{dt}(M/M_0) = C(M/M_0)^{\alpha'}, \ (\alpha' = \alpha + \alpha_1 + 1) \tag{30}$$

$$C = (A_L/10^8 M.c^2) x_0 (\langle\sigma\beta\rangle/10^{-27}\ \text{cm}^2)(\zeta_s/\zeta_n) \tag{31}$$

$$\tau_3 = C^{-1} \approx 1.4 \times 10^8 (x_0)^{-1} (\langle\sigma\beta\rangle/10^{-27}\ \text{cm}^2)^{-1}\ \text{yr}, \tag{32}$$

where we have used $\zeta_{s,0}/\zeta_n \sim 214$.

The solutions to Equation (30) are similar to case (1a) and (1b) considered above for $\alpha' = 1$ or $\alpha' \neq 1$ respectively.

(i) If $\alpha' \neq 1$, we have

$$M/M_0 = [1 - (1 - \alpha')(t/\tau)]^{1/(1-\alpha')} \tag{33}$$

$$L \propto M^{\alpha'}, \ L/L_0 = [1 - (1 - \alpha')(t/\tau)]^{\alpha'/(1-\alpha')}. \tag{34}$$

(ii) If $\alpha' = 1$, we obtain the simple evolution law for the mass and luminosity

$$M = M_0 e^{-t/\tau}, \ L = L_0 e^{-t/\tau}. \tag{35}$$

In conclusion, we summarize our results briefly as follows. The new evolutionary model that we propose for quasars and AGNs may be classified into three groups according to their mass and luminosity:

(1) exponential decay $M, L \propto e^{-t/\tau}$ (see (21), (29), and (35));
(2) $M \propto [1-(1-\alpha)t/\tau]^{1/(1-\alpha)}$, $L \propto M^{\alpha}$ (see (17)–(19), and (24)–(33));
(3) $M \propto [1+\alpha t/\tau]^{-1/\alpha}$, $L \propto M^{\alpha+1}$ (see (27)–(28)).

5. Discussion

We will now discuss the physical significance of our model in more detail and elaborate on the possible implications.

1. As mentioned previously, the RC effect is assumed to be the sole energy source for quasars and AGNs. In other words, the magnetic monopoles contained in these supermassive stellar objects must be Newtonian saturated at least. Therefore, the evolution of the mass and luminosity of these huge stellar objects would follow one of the Equations (27)–(35) as considered in Section 4, case [2] with $\zeta \geq \zeta_s$.

It is expected that the primordial mass of supermassive stellar objects such as quasars and AGNs is so huge that it is compressed by general relativistic effect to $R \leq R_g$. The evolutionary scenario may be depicted by Equations (33)–(34) or (35). The time scale τ_3 for evolution is determined by Equation (32) which corresponds to case (2a). This time scale is considerably shorter than both the time scale τ_1, given by Equation (16), of case [1], and the time scale τ_2, given by Equation (26), of case (2a). Using the estimates given by Callen (1982) and by Rubakov (1983), $\frac{\langle\sigma\beta\rangle}{10^{-27}\ \mathrm{cm}^2} \approx 1$, the evolutionary time scale is only 10^8 years. Thus, the evolution of quasars and AGNs during the early phase is fast. Moreover, the striking activity of quasars and AGNs is most likely also related to the RC effect in view of the large number of high energy particles emitted following nucleon decay induced by magnetic monopoles.

Whereas the mass of these supermassive stellar objects continues to decrease such that $M \leq 10^9 M_\odot$, the radius of such objects may still be much larger than the Schwarzschild radius (Peng *et al.*, 1986). In this case, the evolution may be described by the equations presented in case (2a) and the evolutionary time scale τ_2 is given by Equation (26). Thus, the evolution of quasars and AGNs during the late phase are slow. After the mass of the supermassive stellar objects has reduced to the size comparable to the mass of normal galactic nuclei, the evolution becomes slower and they are no longer active. The resulting massive objects become normal galactic nuclei.

2. In our model for quasars and AGNs, the mass for the primordial supermassive galactic nuclei used is $10^{12} M_\odot$ (roughly the mass of the central black hole for most distant quasars). On the other hand, it is generally believed that the mass of the central black hole in our galaxy is $10^7 M_\odot$. This means that if we take the typical

mass of $10^7 M.$ for massive galactic nuclei at the present epoch, then during the age of the universe of 10^{10} years, the primordial supermassive stellar objects have reduced their mass from $10^{12} M.$ to $10^7 M.$. If we use the fast evolutionary model of Equation (35) to estimate the time scale, we then get $\tau_3 \approx 10^9$ years. The cross-section for the RC effect may be estimated by using Equation (32), namely,

$$x_0 \frac{\langle \sigma\beta \rangle}{10^{-27}\ \mathrm{cm}^2} \approx 1.4 \times 10^{-2}. \tag{36}$$

Of course, the evolution of quasars and AGNs is much more complicated than that described above. In fact, the initial phase of the evolution is very fast, and is then followed by slow evolution. Thus, the estimation given above is only in the order of magnitude indications. Nevertheless Equation (36) gives a very rough estimate of the cross-section for the RC effect in particle physics.

3. Although the primary energy source for the supermassive stellar objects is derived solely from the RC effect, nevertheless, we do not rule out the possibility that there is an accreting disk around the central supermassive galactic nuclei. As emphasized before, during the early phase of fast evolution, the mass of the supermassive stellar objects may be in the range of $10^{10} M. - 10^{12} M.$, and the radii of these superdense objects are comparable to the Schwarzschild radius. Consequently, the strong gravitational effects outside these compact and supermassive stellar objects are similar to usual massive black holes. The prediction of our model compared with the usual black hole model may ultimately be tested by observation, particularly in the infrared region of the electromagnetic spectrum. Recent observational evidence supports the idea that all quasars and AGNs are strong sources of infrared radiation. The emission of such strong radiation is usually explained by assuming the accumulation of dust in the accretion disk around the central black hole. The distinctive feature of this theory is the prediction of a non-thermal power law spectrum. In contrast, in addition to the anticipation for both the presence of a radial magnetic field and the emission of a large number of high energy particles, our model also predicts the usual thermal radiation spectrum. Although the surface temperature of our model for the huge stellar objects is not high (Peng *et al.*, 1986), it is certainly a strong source for infrared radiation. Moreover, in our model for supermassive stellar objects, the spectrum of infrared radiation is simply the Planck spectrum as opposed to the power law spectrum in current models.

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