CONTENT OF MAGNETIC MONOPOLES IN QUASARS, GALACTIC NUCLEI AND STARS AND THEIR ASTROPHYSICAL EFFECTS

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ABSTRACT

Estimations of the number of monopoles preserved and captured in the formation process of quasars, galactic nuclei and stars have been presented here. (i) The monopoles in quasars and other galactic nuclei are preserved in their formation process. And monopole content, \( \xi = N_m/N_\alpha \), may be larger than the Newton saturation value, i.e., \( \xi \gg \xi_m = (2 \times 10^{-10}) \). (ii) The monopoles in normal stars (including the sun), planets (e.g., the earth) and compact stars (white dwarfs and neutron stars) are mainly captured. For normal stars and planets \( \xi \ll \xi_m \) for white dwarfs and neutron stars either \( \xi \approx \xi_m \) if the cross section of the Rubakov-Callan effect is much larger than \( 10^{-10} \gamma, \gamma = \gamma_\alpha/10^{-10} \), or \( \xi \approx \xi_m \) if not. (iii) The monopoles in the center of the objects produce a radially magnetic field. The detection of the field may give limitations to the cross section of the RC effect.

I. INTRODUCTION

The grand unified theories suggest the possibility of the existence of massive monopoles \((M_m \sim 10^{10} \text{GeV}/c^2)\) of the 't Hooft-Polyakov type. Recently, Z-Q. Ma and J-F. Tang obtained the solution to the stable colorless monopole\(^{21}\) whose magnetic charge is three times as large as the Dirac magnetic charge, \(g_m = 3e/2c\). In inflationary cosmology, the oscillation and the thermal fluctuation of the Higgs field may produce an amount of monopoles during the phase transition of the early universe\(^{22}\). Parker and Lazarides et al. gave an upper limit to the ratio of number of monopoles to nucleon: \(\xi = (N_m/N_\alpha) \ll 10^{-37}\). Rubakov and Callan recently presented monopole catalysis of nucleon decay (hereinafter RC effect).

\[
PM \rightarrow e^+XM(85\%) \text{ or } PM \rightarrow e\mu^+ \mu X(15\%),
\]

where \(X\) is electron-neutral mesons \(D^0, \omega\) and \(\rho\). The cross section of the catalyzed nucleon decay reaches the order of over of strong interaction, \(\sigma \sim 10^{-12} \text{ to } 10^{-24} \text{ cm}^2\). However, there has been much controversy over whether the RC effect does exist and what is the value of the cross section. A recent research by Ma Zhongqi and Tang Jufei on the motion of fermion in the monopole field supports again the concept and dismisses Walsh's doubts\(^{27}\).

II. MONOPOLES IN ORIGINAL CLOUDS

There may be strong turbulence in the early universe, therefore there may be strong local magnetic field, the order of magnitude of \(10^{-7} \sim 10^{-10} \text{ Gs}\). In the strong field of the early universe, positive and negative monopoles move in opposite directions\(^{21}\). It causes separation of these two kinds of monopoles from each other. If the scale of the separation is larger than that of the density fluctuation, we can reasonably assume that there is only one kind of monopole, either positive or negative, in original nebulae, therefore, in the present objects.

As a nebula collapses, the massive monopoles settle gradually in the center of the object. But the magnetic Coulomb repulsion between similar polar monopoles prevents them from continual centering.

Let \(R_m\) represent the radius of monopole-concentration region, where one monopole suffers two balances: the Newtonian gravitation from the total mass in the region and the Coulomb repulsion from the total magnetic charge in the region. We can derive the number ratio of monopoles to nucleons in the spherical region under the balance condition.

\[
\xi = N_m/N_\alpha = Gm_m n/n_\alpha \approx 1.9 \times 10^{-27},
\]

It is independent of the radius and total mass. If \(R_m\) equals \(R\), we have the same result, which we call the Newton saturation value.

III. MOTION OF MONOPOLE IN CONTRACTION PROCESS OF ORIGINAL NEBULA

The original nebula first undergoes the rapid contraction stage. The mass in it falls toward the center at an approximately free-falling velocity, \(V_f(r) = c(R_f/r)^{1/2}\), where \(R_f\) is the Schwarzschild radius. The time scale of contraction is

\[
t_f \sim \left( \frac{32}{5} \pi G \rho \right)^{-1/2} \quad (\text{neglecting the angle momentum and magnetic field in the nebula}).
\]

The average number density, then, is inversely proportional to cube of radius,

\[
n(R) = n_0 (R_0/R)^{3},
\]

where \(n_0\) and \(R_0\) are initial values of \(n\) and \(R\) respectively.

According to the expanding law of the universe, the initial number density of the nebula is

\[
n_0 = \beta \frac{2\pi}{m_m} \left( \frac{T_0}{T} \right)^{3/2} = 0.4 \beta G,
\]
where $T_c (\approx 4 \times 10^4 \text{K})$ and $T_p (\approx 2.7 \text{K})$ are background temperatures in the era of formation of galaxies and today respectively. $\beta (\geq 1)$ is the ratio of average density of the original nebula to the average density of the universe at that time. And $\Omega$ is the ratio of average $\rho_0$ of the present universe to the critical density $\rho_c = 1.1 \times 10^{-30} (H_0/75)^2 \text{g/cm}^3$.

The time scale of the nebula collapse is $3 \times 10^5$ years. Due to the high density in the central region of the nebula and the rapid contraction, a galactic nucleus forms there. As nuclear temperatures rise because of the contraction, the thermonuclear reaction begins. In addition to the strong luminosity produced by the thermonuclear reaction, the inward falling mass releases a large amount of energy. When the total luminosity exceeds the Eddington limit, strong radiation protects the external part of the nebula from collapse.

The above description is a general case. However, if there exist monopoles, the situation is different. The interaction between monopoles and matter is very weak. And the number density of monopoles is so small that the collision between monopoles can be neglected. The Keplerian orbits of monopoles around the center alter very slowly. The time scale is as long as the age of the universe or more than that unless mass distributed on the orbit is very dense. It cannot be simply presumed that monopoles and other matters fall together at a free-falling velocity. We must study the interaction between monopoles and matter and analyze how monopoles fall toward the center of objects, in order to estimate the monopole number in the objects.

The monopoles moving in medium will excite a turbulent electric field. For the central medium, this field may make neighboring atoms excited or ionize, which consumes kinetic energy of monopoles at a rate

$$- \frac{dE}{dx} = \left(9n^2/m_e Z A \right) v_m^2 \Lambda, \quad \Lambda = \ln \left( \frac{2m_e v_m^3}{R} \right).$$

where $n$ is the number density of central atoms with atomic number $Z$, $E$ is a Rydberg constant (in frequency), and $v_m$ is the velocity of monopoles in the medium. For the cloud of central hydrogen, the above formula becomes

$$- \frac{dE}{dx} \sim \alpha v_m^2 \text{erg/cm}, \quad \alpha \sim 1.4 \times 10^{-31}.$$  \hspace{1cm} (2)

In the plasma medium, the turbulent electric field excited by moving monopoles induces plasma oscillations. It consumes kinetic energy of monopoles at a rate

$$- \frac{dE}{dx} = \frac{2v_m^2 v_e A}{3v_c^2} \lambda,$$

where $\lambda_d$ is the Debye radius, $v_e$ is the thermal velocity of electron, and $A$ is the Coulomb logarithm.

$$\lambda_d = \left( k_B T / 4 \pi n_e e^2 \right)^{1/2}, \quad v_e = \left( k_B T / m_e \right)^{1/2} \text{and} \quad A \sim 10.$$  \hspace{1cm} (3)

And this formula becomes

$$\frac{dE}{dx} \sim \alpha v_m^2 \text{erg/cm}, \quad \alpha \sim 5.4 \times 10^{-31}. $$

Similar to friction, the interaction between monopoles and mass tends to make monopoles moving with mass. In the rest frame, even monopoles move outward or along tangent, they will finally move inward if the interaction is strong enough.

Let $v_n$ be the initial velocity of monopoles, $v_n = c(R/R)^2 v_0$ be the velocity of mass falling inward at radius $R$. Then the velocity of monopoles relative to mass is $v_m = v_n - v_0$. When nebula contracts to some extent, $v_n < v_f$ and $v_m < v_0$.

Assuming that after monopoles moving for distance $l$, their outward and tangentially kinetic energy is consumed by "friction" and they only fall inward, then we have

$$l \sim \frac{1}{2} m_e v_m^2 / \left( - \frac{dE}{dx} \right).$$

Replacing $- \frac{dE}{dx}$ by formula (2) and (3), we obtain

$$l_p \sim \frac{1}{2} \alpha v_m^2 \text{cm}, \quad v_m = v_n = c(R/R)^2 v_0 \text{cm}$$  \hspace{1cm} (4)

for the plasma nebula and

$$l_h \sim \frac{1}{2} \alpha v_m^2 \text{cm}, \quad v_m = v_n = c(R/R)^2 v_0 \text{cm}$$  \hspace{1cm} (5)

for the central hydrogen nebula.

IV. The Number of Monopoles Contained in an Object During Formation

The relation between the number density of nucleus in the nebula and its radius is

$$R_n = \left( \frac{3 M_n}{d x} \right)^{1/3}$$

or

$$R_n/R_c \approx 3.1 \times 10^5 M_n^{1/3} n_0^{-1/3},$$

where $M_{tot}$ is the mass of the nebula in unit $10^3 M_\odot$. When the nebula contracts to radius $R$, the average number density of nucleus

$$n(R) = 2.9 \times 10^6 c(R/R)^{3} M_n^{2/3} \text{cm}^{-3},$$

then formulae (4) and (5) become

$$l_p \sim 9.6 \times 10^3 c(R/R)^{2} M_n^{1/3} \text{cm}, \quad l_p \sim 1.1 \times 10^3 c(R/R)^{2} M_n^{1/3} \text{cm},$$

where $n = n_i / n_0$ is the degree of ionization in the nebula.

When the nebula contracts to radius $R$, which satisfies relation

$$l \leq b R / \theta, \quad (\theta = 1/3 - 1/5).$$
we consider that all monopoles with outward velocity \( v < v_m \) within radius \( R_e \) are drawn back by collapsing and fall into the center of the nebula at a free-fall velocity. Thus the number of monopoles in galactic nuclei and stars is equal to that within \( R_e \) in the original nebula, i.e.

\[
N_m = N_m^c(R_e/R_b)^7,
\]

(10)

where \( N_m^c \) is the total number of monopoles in the original nebula. From \( l \ll b \), and formulae (8), (9), \( R_e \) can be estimated

\[
(R_e/R_b) \approx 2.3 \times 10^{4}(a_b)^{5/2}M_2^{-3/2}T^{-1}(v_m/10^{-4}c)^{-4/3},
\]

(11)

\[
(R_e/R_b) \approx 5.2 \times 10^{2}M_2^{-1/2}T^{1/2}(v_m/10^{-4}c)^{-1}.
\]

(12)

Combining (6), (10)\(- (12)\), we obtain

\[
(N_m/N_m^c)_a \approx 3.1 \times 10^{-3}(a_b)^{n_T}T^{-1}(v_m/10^{-4}c)^{-4}
\]

(13)

for plasma, and

\[
(N_m/N_m^c)_a \approx 4.7 \times 10^{-3}b^{4/5}a_mM_2^{1/5}(v_m/10^{-4}c)^{-3}
\]

(14)

for the central hydrogen cloud.

The contraction of nebula begins in the recombination epoch at temperature \( T \), about \( 4 \times 10^{10}K \), with number density of hydrogen atoms \( n = 0.49 \). Then formula (13) is applicable to this case.

Assuming that the mass of galactic nucleus equals \( \tau \) times that of nebula, \( \tau \sim 10^3 \), the ratio of number of monopoles to nucleon

\[
\xi = N_m/(\tau M_4/m_4) = \tau^{-1}v_m(N_m/N_n^c) \sim \tau^{-1}v_m(N_m/N_n^c),
\]

i.e.

\[
\xi/\xi_n \sim 3.1 \times 10^{-2}r^{-1}\beta -1/2(\beta/\beta r)(v_m/10^{-4}c)^{-1} \sim 10^{2}(\tau/10^3)^{-1}(\beta/\beta r)(v_m/10^{-4}c)^{-1}.
\]

(15)

The velocity of monopoles in the interstellar space in the galaxy is probably \( 10^2 \) c today\(10^5 \). In the early universe, it may be less than the value\(4 \), for example, \( v_m < 10^4 c \). Then the monopole content in the objects may reach or exceed the Newton saturation value.

For stars, things are different. In the original nebula, \( T = 10 \sim 1000 K, \in \sim 10^8 \sim 10^{10} \text{cm}^{-1}. \) The mass is in the neutral state. It is believed that stars, at least the population I, were formed after the formation of the galaxy and the physical condition in the nebula-formed stars was similar to today’s in the interstellar space in which the velocity of monopoles is about \( 10^3 c. \) Moreover, it is usually considered that the ratio of mass of star to the nebula is

\[
\tau' = M/M_4 \sim (3 \sim 10^{13}).
\]

Therefore,

\[
\xi/\xi_n \sim (\tau')^{-1}(N_m/N_n^c) \sim 4.7 \times 10^{-4}(\tau')^{-1/2}(v_m/10^4M_4/M)(v_m/10^{-4}c)^{-1}.
\]

(16)

It partly depends on the stellar mass: \( \xi/\xi_n \sim 10^{-19} \) for the sun. If the earth was formed from the same cloud, \( \xi/\xi_n \sim 8 \times 10^{-16} \).

V. Monopoles Captured by Objects

The number of monopoles captured by objects with mass \( M, \) radius \( R, \) and the age \( r \)

\[
N_m^c = \eta \cdot 4\pi \Phi \cdot 4\pi R^2[1 + c(a_b/a_m)]r,
\]

(17)

where \( v_m = c (R/R_b) v^2 \) is the escaping velocity on the surface of the objects. The second term from accretion theory\(4 \) is much smaller than \( 1 \) for planets. It is about \( 1 \) for normal stars, and is much larger than \( 1 \) for compact objects, e.g. dwarfs and neutron stars and active galactic nuclei. The ratio is

\[
\zeta = N_m^c/N_m^c = 5.1 \times 10^{-2}a_m[1 + 10^{3.5}(a_m/a_m)](R/R_b)(\Phi/\Phi r)(r/10^9)
\]

(18)

where \( \Phi \) is the flux of monopoles, \( \Phi_0 \) is the Parker limit \( \approx 10^{-26} \text{cm}^{-2} \) for \( 1 \) electron\(10^{-17} \) and \( \eta \) is the probability that object captures monopoles, depending on the ratio of penetrating distance of monopoles to radius of the object.

\[
\eta \sim R/1^2
\]

where the penetrating distance

\[
i = v_m t \sim a_m(—d_R/dx).
\]

In the neutral medium\(10^3 \),

\[
i_0 \sim 4.8 \times 10^{10}N(m/10^{-3}c)^{1/2} \text{cm}.
\]

And in plasma,

\[
i_0 \sim 1.2 \times 10^{10}(a_m/10^{-3}c)M_4^{-1/2}T^{1/2} \text{cm}.
\]

According to (12) and (13), the upper limit of monopole flux in interstellar space is

\[
\eta_0 \leq (\tau_0 \sim 10^{-1})^{1/2}(\tau_0 \sim 10^{-7})^{-1}.
\]

(19)

From (18) we obtain

\[
\zeta^{10} \leq (10^{-19} \sim 10^{-8})M_4((M_4/10)^{-1}(a_b/a_m)^{-1}.
\]

(20)

for quasars and galactic nuclei;

\[
\zeta^{10} \leq (10^{-15} \sim 10^{-8})M_4((M_4/10)^{-1}(a_b/a_m)^{-1} (\tau/10^9)
\]

(21)

for the sun and ordinary stars;

\[
\zeta^{10} \leq (10^{-21} \sim 10^{-8})M_4((M_4/10)^{-1}(a_b/a_m)^{-1} (\tau/10^9)
\]

(22)

for dwarfs and neutron stars.

VI. DISCUSSION

1. The monopoles in quasars and other galactic nuclei are mostly preserved in their formation process. If \( R/R_b > 1, \) the \( \zeta \) is \( \zeta_n \) and if \( R/R_b \ll 1, \) the \( \zeta > \zeta_n \) or \( \zeta > \zeta_0.\)
where $\xi \sim 10^{-29}$ is the Newtonian saturation value.

2. Normal stars such as the sun and planets such as the earth mainly captured their monopoles. Whether $\langle \sigma \rho \rangle/10^{-7} \sim 1$ or $10^{-20}$, we have $\xi \ll \xi_0$. Owing to the supermassiveness of monopoles, they fall into the center of the object. It, therefore, is impossible to search monopoles on the surface of the earth, the moon and other planets or meteoric matter\(^{19}\).

3. The monopoles in compact objects, e.g., dwarfs and neutron stars, are captive. If $\langle \sigma \rho \rangle/10^{-7} \sim 1$, $\xi/\xi_0 < 10^3 - 10^5$ for dwarfs and $\xi/\xi_0 < 1$ for neutron stars. However, if $\langle \sigma \rho \rangle/10^{-20} \sim 10^{-27}$, $\xi \sim \xi_0$ for both dwarfs and neutron stars.

4. The radial field intensity produced by monopoles is

$$H_n(R) = \frac{N_m}{R^2} \sim 1.1 \times 10^{-6} \xi_0/\xi (M/R^2).$$  \tag{29}

For the sun and planets (including the earth) it is

$$H_n(R) \leq (10^{-7} - 10^{-8})(\sigma \rho/10^{-7})^{-1} (r/10^6) \text{ Gs.} \tag{24}$$

If $\langle \sigma \rho \rangle/10^{-7} \sim 10^{-1}$, $H_n(R)$ is very small, but if $\langle \sigma \rho \rangle/10^{-20} \sim 10^{-27}$, $H_n(R) \sim 1$ Gs. For neutron stars and dwarfs they are respectively

$$H_n^{\text{ne}}(R) \sim 2.2 \times 10^{-2} \xi_0/\xi (M/M_\odot)(R/10 \text{ km})^{-2} \text{ Gs} \tag{26}$$

and

$$H_n^{\text{dw}}(R) \sim 2.2 \times 10^{-2} (\xi/\xi_0) (M/M_\odot)(R/10^4 \text{ km})^{-3} \text{ Gs.} \tag{26}$$

From (22), (25) and (26), we obtain

$$H_n^{\text{ne}}(R) \sim 10^{-12} (r/10^6 \text{ yr}) \text{ Gs,}$$

which is less than observational intensity on pulsars and

$$H_n^{\text{dw}}(R) \sim 10^{-2} (r/10^6 \text{ yr}) \text{ Gs,}$$

which seems to show there is probably a magnetic field not to be too weak on the surface of the old dwarfs.

If $\langle \sigma \rho \rangle/10^{-20} \sim 10^{-27}$ and the flux of monopole in interstellar space

$$\Phi/\Phi_0 \sim (10^{-1} - 10^{-2})(\sigma \rho/10^{-20})^{-1},$$

there will be so many monopoles in neutron stars and dwarfs that $\xi \sim \xi_0$. And then

$$H_n^{\text{ne}}(R) \sim 10^4 \text{ Gs,}$$

which is inconsistent with observations on pulsars. The inconsistence implies either

$$(\Phi/\Phi_0)(\sigma \rho/10^{-20}) \sim 10^{-13} \sim 10^{-14}$$

or

$$\langle \sigma \rho \rangle/10^{-20} \sim 1.$$}

Therefore, the measurement of the field intensity on the objects places a restriction on the cross section of RC effect and flux of monopoles.

5. The luminosity due to monopole-induced nucleon decay is

$$L_n = \int_{R_n} \int_{R_n} 4\pi r^2 \phi \rho \epsilon_0 n_0^2(r) m_0^2.$$

Based on the luminosity and other considerations, we made assumptions on the energy source for nucleus of the earth\(^{15}\) and proposed a model for nucleus of the galaxy and other galaxies\(^{20}\). We also explained the positron-electron annihilation line in the galactic center\(^{17}\).

6. In this paper, only one kind of monopole, either N-pole or S-pole, was involved. If both kinds are considered, the above conclusions can be drawn only by using difference between N- and S-monopole numbers instead of $N_0^+ N_0^-$ in formula (15). And monopole induced by nucleon decay will be more effective in that case.

REFERENCES

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