On Spectrum of Extremely High Energy Cosmic Rays through Decay of Superheavy Particles

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Abstract

We propose a formula for flux of extremely high energy cosmic rays (EHECR) through decay of superheavy particles. It is shown that EHECR spectrum reported by AGASA is reproduced by the formula. The presence of EHECR suggests, according to this approach, the existence of superheavy particles with mass of about 7×10^{11}GeV and the lifetime of about 10^9 years. Possibility to obtain a knowledge of Ω_0 of the universe from the spectrum of EHECR is also pointed out.

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The unexpected energy spectrum of the extremely high energy cosmic rays (EHECR) with the energy above $10^{19.8}$eV has been reported by Akeno Giant Air Shower Array (AGASA) collaboration which used the updated data set[1]. The existence of EHECR has been known for about 30 years [2], among which the highest energy of EHECR, $(3.2 \pm 0.9) \times 10^{20}$eV, was recorded in Fly's Eye [3]. When we regard nucleons or nuclei as constituents of EHECR, the attenuation length is estimated less than ~ 100 Mpc due to Greisen-Zatsepin-Kuz'min (GZK) effect [4, 5]. Thus if distances from Earth to any sources of EHECR are over 100 Mpc, it is difficult to explain EHECR in terms of nucleons or nuclei. One may expect that sources of EHECR would exist within about 100 Mpc from Earth, but such sources have not been found. Here we can make a brief list of yet unsolved problems on EHECR as follows: (1) the chemical compositions of EHECR are unknown, (2) the sources of EHECR are unclarified, and (3) the shape of energy spectrum reported by AGASA is unexplained.

In order to solve these problems, several ideas have been proposed. There exist mainly two approaches based on astrophysical aspect and particle physical aspect. From the astrophysical aspect, number of acceleration mechanisms of the ordinary particles have been proposed. For example, the protons are accelerated to the extremely high energy by the relativistic jets from AGN [6]. The production of EHECR by the Gamma-Ray Bursts is also considered [7]. There are, however, no particular astronomical objects in the directions of EHECR [1, 3].

On the other hand, from the particle physical aspect, the production mechanism of EHECR has been proposed [8]. A basic idea is that EHECR are produced by decay of superheavy particles. In this case, EHECR are consisted of either the standard particles (proton, photon or neutrino) or the new particles (for example, neutralino or gluino). Furthermore, instead of decay products of superheavy particles, quasi-stable superheavy particles can also be considered as constituent of EHECR in itself. For example, colored monopoles have been examined in ref.[9].

When decaying superheavy particles are considered as sources of EHECR, it is plausible to imagine the mass of the superheavy particles larger than about 10^{12}GeV, since the highest energy of EHECR is $(3.2 \pm 0.9) \times 10^{20}$eV. There are many models in particle physics which introduce such superheavy particles, for example, supersymmetric grand unified theory or the see-saw model for neutrino mass. However, the superheavy particles that should decay into EHECR have to have a long lifetime which is nearly or greater than the present age of the universe, because, if the superheavy particles decay fast, the remnants of the superheavy particles are very little, and as a result, we cannot observe EHECR produced via the decay. Although the order of lifetime is usually proportional to the inverse of mass of the particle, some kind of models [10] permits quasi-stable superheavy particles contrary to their heaviness.

It is attractive to make clear of the relation between the EHECR problem and the particle physical aspect, because we can expect that the feature of EHECR leads us to ones beyond the standard model of particle physics with a large mass scale larger than about 10^{12}GeV.

In this paper, we examine the problem of EHECR from the particle physical aspect, although we do not reject at the present time a possibility to explain EHECR from astronomical origins like quasisteller objects which are recently considered seriously in ref. [11]. We propose a proper formula for the flux of EHECR in the beginning. This formula should be used when EHECR are produced via the decay of the superheavy particles. Reproducing the spectrum of EHECR observed at AGASA by using our formula, we show that the lifetime of the superheavy particles is suggested to be about 10% of the Hubble time when their mass is 7×10^{11}GeV. Furthermore, it is also pointed out that the possibility to obtain a knowledge of the omega parameter, Ω_0, of the universe from the energy spectrum of EHECR.

At first, we show the formula for the flux to the cosmic rays as decay products of superheavy particle X. Let f be the particle in decay products of X and produce Extensive Air Showers (EAS) when it reaches to the atmosphere. We denote the number density of the source at time t_e as $n_X(t_e)$ and the partial decay constant for a decay mode including f as Γ_f. Then the production rate of f at time t_e is determined by $\Gamma_f n_X(t_e)$. The general expression of the flux of cosmic rays, after taking average about the angular distribution, is given in the Robertson-Walker metric with the scale factor $a(t)$ as follows:

$$J(E_{obs}) \;=\; \frac{1}{4\pi}\int_{t_{min}}^{t_0} \mathrm{d}t_e \left(\frac{a(t_e)}{a(t_0)}\right)^3 n_X(t_e)\frac{\mathrm{d}\Gamma_f}{\mathrm{d}E_e}\frac{\mathrm{d}E_e}{\mathrm{d}E_{obs}}\ , \tag{1}$$

where E_{obs} is the observed primary energy of cosmic rays, and $\mathrm{d}\Gamma_f/\mathrm{d}E_e$ is the energy distribution of cosmic rays emitted by the source at time t_e. The present time is represented by t_0, while t_{min}, is determined by a physical condition that $t_0 - t_{min}$ is smaller than an attenuation time of f.

The number density of the superheavy particles $n_X(t)$ is evolved by the following Boltzman equation,

$$\frac{\mathrm{d}(a(t)^3 n_X(t))}{\mathrm{d}t} = -\Gamma_X a(t)^3 n_X(t), \tag{2}$$

where Γ_X is total decay width of X. This equation gives

$$n_X(t) = \left(\frac{a(t_0)}{a(t)}\right)^3 n_X(t_0)\exp[\Gamma_X(t_0 - t)]\,. \tag{3}$$

By substituting eq. (3) into eq. (1), we obtain

$$J(E_{obs}) \;=\; \frac{n_X(t_0)}{4\pi}\int_{t_{min}}^{t_0} \mathrm{d}t_e \exp[\Gamma_X(t_0 - t_e)]\frac{\mathrm{d}\Gamma_f}{\mathrm{d}E_e}\frac{\mathrm{d}E_e}{\mathrm{d}E_{obs}}\ . \tag{4}$$

Here we would like to make a comment on this formula. In the previous works, similar formulae have been used [8, 12]; however, the effect of the decrease in the number density of parent particles has been neglected, since their lifetime has been assumed to be greater than the age of the universe. On the other hand, in eq. (4), this effect is included in the form of exponential damping factor, $\exp[\Gamma_X(t_0 - t)]$, since X is supposed to have the same order lifetime as the present age of the universe. We should use eq. (4) rather than the formula used in previous works when we estimate the flux of EHECR produced by the decay of superheavy particles. This is because the number density of parent particles decreases due to their decay. This effect is very important to reproduce the spectrum of EHECR as shown later in this paper.

Our formula, eq. (4), can be applied to the case that f can travel almost freely through the cosmic background radiation, though the attenuation due to the GZK effect has been neglected. For example, we can take f to be neutrino or neutralino. The difference between them is the translation rate R_{c2a} of EHECR to EAS when they reach at Earth and produce EAS.

$$R_{c2a} \equiv \frac{\text{number of EHE air shower events}}{\text{number of EHECR incident on Earth}} . \tag{5}$$

Then the flux of EAS, $J(E_{obs})|_{\rm EAS}$, is derived from the flux of EHECR, $J(E_{obs})|_{\rm EHECR}$, as

$$J(E_{obs})|_{\rm EAS} = J(E_{obs})|_{\rm EHECR} R_{c2a}. \tag{6}$$

Neutrino gives the translation rate larger value as an order of $R_{c2a} = 10^{-6}$ [13] than neutralino.

Now we consider a case that EHECR are taken to be neutrinos which are produced by the two-body decay of X. Its mass, M_X, can be expected about twice the highest energy of EHECR. Since the highest energy recorded by Fly's Eye is $(3.2\pm0.9)\times10^{20}$eV, we take M_X as 7×10^{11}GeV in the following. The energy spectrum right at the emitted point is to be the monochromatic one in the two-body decay,

$$\frac{{\rm d}\Gamma_f}{{\rm d}E_e} = \Gamma_f\, \delta(E_e - M_X/2). \tag{7}$$

Hereafter, for simplicity, we limit ourselves to consider such a case that there is unique channel for two-body decay, *i.e.* $X \to \nu +$ some particle, and then Γ_f becomes just the total decay width Γ_{tot}. Since the kinematics tells that the energy spectrum is monochromatic in the present case, we can obtain the energy distribution of EHECR without the detailed description of the interaction. Thus we will be able to discuss the problem of EHECR rather in the model-independent way.

The red-shift relation between E_e and E_{obs} is represented as $(1+z)E_{obs} = E_e$. Then the monochromatic energy condition becomes

$$\delta(E_e - M_X/2) = \frac{1}{E_{obs}} \frac{1}{|{\rm d}f(t)/{\rm d}t|} \delta(t - t_\alpha)\theta(z), \tag{8}$$

where the step function $\theta(z)$ is necessary to satisfy the condition $z \geq 0$. In eq. (8), $f(t) \equiv 1+z(t)$, and t_α is defined as a solution of $f(t_\alpha) = M_X/2E_{obs}$. The expression of $f(t)$ is different for each of three cases, open universe of $\Omega_0 < 1$, flat universe of $\Omega_0 = 1$ and closed universe of $\Omega_0 > 1$. By using eqs. (4) $\sim$ (8), we can calculate the energy spectrum of EHECR. For the moment, we consider the case for $\Omega_0 = 1$, where $f(t) = (t_0/t)^{2/3}$. In this case, the spectrum of EAS is given by

$$J(E_{obs})\,|_{\rm EAS} = R_{c2a} n_X(t_0) \frac{\sqrt{2}\Gamma_X}{2\pi H_0} \frac{\sqrt{E_{obs}}}{{M_X}^{3/2}} \exp\left\{ \frac{2\Gamma_X}{3H_0} \left[1 - \left(\frac{2E_{obs}}{M_X} \right)^{3/2} \right] \right\} . \tag{9}$$

The AGASA's data above the GZK cutoff [1] distributes over the energy region from $10^{19.8}$eV to $10^{20.5}$eV, which corresponds to the change of 1 to 5 for $1+z$. This means that the most remote position of X is about 7 Gpc in flat universe case. This distance is certainly shorter than the mean free length of supposed neutrinos on the collisions with background photons or neutrinos [14]. Thus we can practically put t_{min} into 0 in eq. (4). We see from eq. (9) that the spectrum of EHECR is determined by the three parameters M_X, $r \equiv \Gamma_X/H_0$, and $R_{c2a} n_X(t_0)$. Since R_{c2a} appears as a product with $n_X(t_0)$ in eq. (9), fortunately an ambiguity of R_{c2a} does not affect our estimate of the spectrum. When we reproduce the spectrum reported by AGASA, we must multiply the factor E_{obs}^3 to eq. (9).

Fig. 1 displays the curves of $\log_{10}(J(E_{obs})E_{obs}^3)$ for the case that EHECR are to be neutrinos produced by the two-body decay of X. The flux $J(E_{obs})$ is calculated by eq. (9). The end point of the energy spectrum locates at $M_X/2$. The energy of EHECR produced at time t_α is lowered to $E_e/(1+z)$ by the red shift. The peak around 10^{20}eV is reproduced by synergistic effect between the decreasing factor of X, $\exp[\Gamma_X(t_0-t_1)]$, and the expanding factor of the universe, $(t_0/t_1)^{2/3}$ in eq. (4). We see remarkable conformity of the energy spectrum of EHECR by eq. (9) with the one reported by AGASA.

The location of peak of the spectrum shown in Fig. 1 is derived from eq. (9) as

$$E_{obs}(\text{peak}) = \frac{M_X}{2}\left(\frac{3.5}{r}\right)^{2/3}. \tag{10}$$

In order that the peak appears in Fig. 1, $r > 3.5$ is needed. We see from the data point given by AGASA that the peak seems to locate at $E_{obs} \sim 10^{20}$eV, though this location is vague in the data. When the inequalities $20.1 < \log_{10} E_{obs} < 20.4$ are imposed, we obtain

$$3.5\left(\frac{M_X}{2}10^{-11.4}\right)^{1.5} < r < 3.5\left(\frac{M_X}{2}10^{-11.1}\right)^{1.5} \tag{11}$$

where M_X is given in the unit of GeV. For $M_X = 7\times10^{11}$GeV, we find $5.8 < r < 16$. The inequalities turn the lifetime of X into $\tau_X = (0.09 \sim 0.3)\, t_0$.

When we see AGASA's data [1] in detail, there is no event in the energy bin between $10^{20.2}$ and $10^{20.3}$ eV. We anticipate, however, appearing of one event at this energy bin from our present consideration. But if there remains this vacancy in future, this spectrum should be interpreted from our standpoint as a suggestion that two kinds of superheavy particles with different masses exist. The spectrum below $10^{20.2}$ eV is due to superheavy particles with mass of 3×10^{11}GeV, while the one over $10^{20.3}$eV is due to another superheavy particles with mass of 7×10^{11}GeV.

In Fig. 2, the curves of $\log_{10}(J(E_{obs})E_{obs}^3)$ are shown for $\Omega_0 = 0.5, 1$, and 2. We put $r = 10$ for $M_X = 7\times10^{11}$GeV as an example. Statistics of the current data above $10^{19.8}$ eV is not enough to derive information of Ω_0. We hope from this point that the statistics of the EHECR observation increases in future.

So far we have considered two-body decay case. Here we address a question how the energy spectrum changes for multi-body decay case. As an example, we show the curves of $\log_{10}(J(E_{obs})E_{obs}^3)$ for three-body decay due to four-Fermi interaction. We can see from Fig. 3 that the curves for three-body decay case do not reproduce the data so well as those for two-body decay case in Fig. 1.

In summary, we have examined the problem of EHECR from the particle physical aspect, proposing a suitable formula to the flux of the cosmic rays through decay of superheavy particles. Then the energy spectrum of EHECR has been reproduced satisfactorily as that of the neutrinos via two-body decay of X with mass of 7×10^{11}GeV and lifetime of around $0.1\,t_0$. $R_{c2a}\Omega_X(t_0) \sim 10^{-14}$ has been required to reproduce the energy spectrum of EHECR, where $\Omega_X \equiv \rho_X/\rho_{cr}$ as is usually defined. Our analysis is not confined exclusively to the neutrino case as mentioned before. We can take neutralino instead of neutrino. The difference between neutralino and neutrino is only the value of R_{c2a}, and R_{2ca} becomes smaller for neutralino. Thus, $\Omega_X(t_0)$ turns out to be much larger for neutralino case than 10^{-8} for neutrino case. Furthermore, we have the possibility to derive a knowledge of the omega parameter, Ω_0, of the universe from the energy spectrum of EHECR. We expect to acquire further information of superheavy particles as well as Ω_0 of the universe from future observations where more data will be accumulated to give higher statistics. From this aspect, future detectors like the HiRes, the Telescope Array, the Pierre Auger, and the Owl [15] are greatly awaited.

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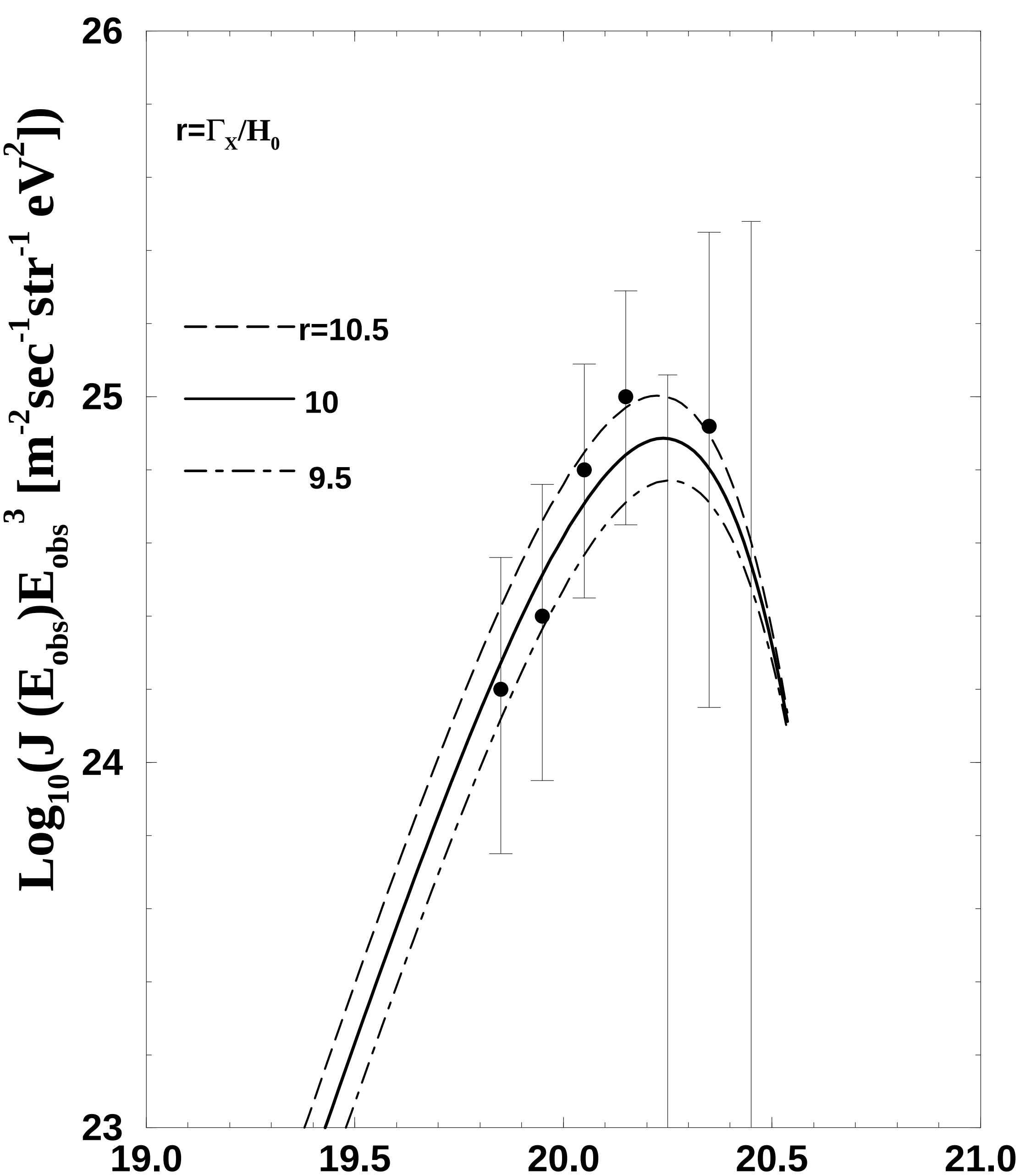

Figure 1: Curves of $J(E_{obs})E_{obs}^3$ for the two-body decay case. Data points and error bars are taken from AGASA data given in [1]. Input parameters are taken as follows; $M_X = 7\times 10^{11}$GeV, $r \equiv \Gamma_X/H_0 = 9.5, 10$, and 10.5, $\Omega_0 = 1$, $\rho_X(t_0) = M_X n_X(t_0) = 10^{-8}\rho_{cr}(t_0)$, and $R_{c2a} = 10^{-6}$.

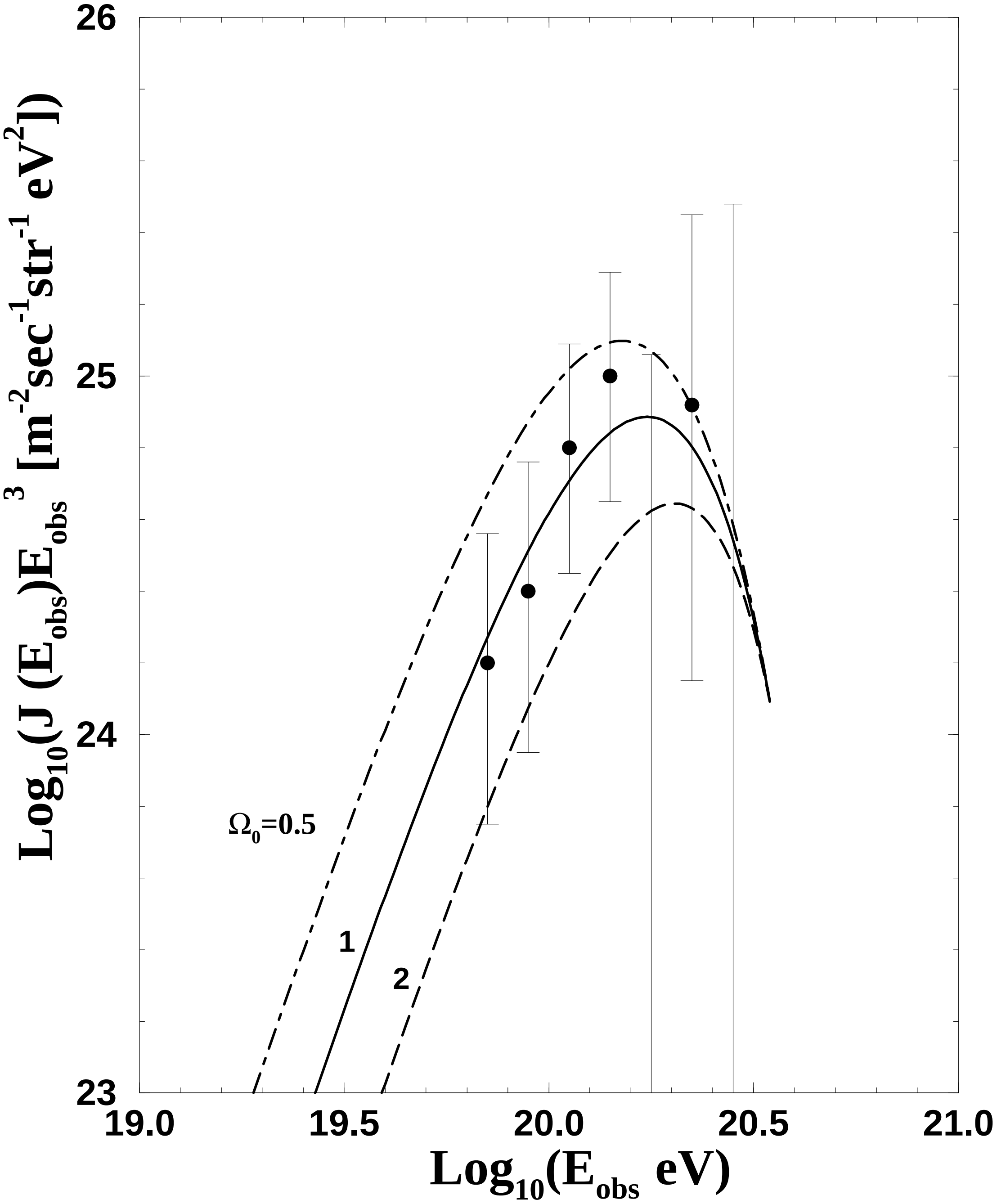

Figure 2: Curves of $J(E_{obs})E_{obs}^3$ for the two-body decay case. We take the omega parameters as $\Omega_0 = 0.5, 1, 2,$ and $r = 10$. Other input parameters are taken to be the same as in Fig. 1.

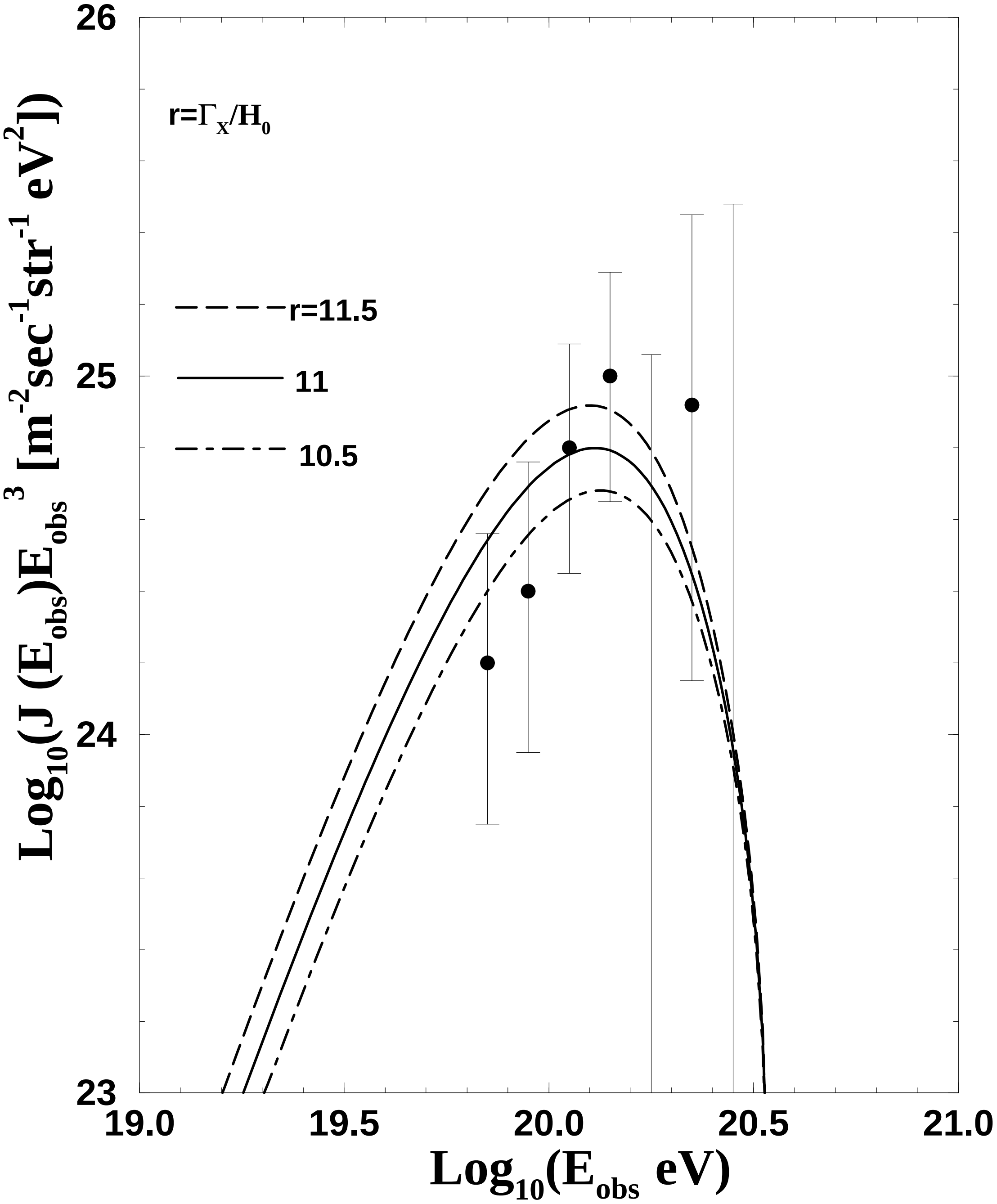

Figure 3: Curves of $J(E_{obs})E_{obs}^3$ for the three-body decay case. We take the ratio of Γ_X/H_0 as $r = 10, 10.5$, and 11.5. Other input parameters are taken to be the same as in Fig. 1.