The contribution of ultracompact dark matter minihalos to the isotropic radio background

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The ultracompact minihalos could be formed during the earlier epoch of the universe. The dark matter annihilation within them is very strong due to the steep density profile, $\rho \sim r^{-2.25}$. The high energy electrons and positrons from the dark matter annihilation can inverse Compton scatter (ICS) with the background photons, such as CMB photons, to acquire higher energy. On the other hand, the synchrotron radiation can also be produced when they meet the magnetic field. In this paper, we study the signals from the UCMHs due to the dark matter annihilation for the radio, X-ray and $\gamma$-ray band. We found that for the radio emission the UCMHs can provide one kind of source for the radio excess observed by ARCADE 2. But the X-ray signals due to the ICS effect or the $\gamma$-ray signals mainly due to the prompt emission from dark matter would exceed the present observations, such as Fermi, COMPTEL and CHANDRA. We found that the strongest limits on the fraction of UCMHs come from the X-ray observations and the constraints from the radio data are the weakest.

I. INTRODUCTION

It has been confirmed by many observations and theoretical research that the present structures of our universe come from the earlier density perturbations $\delta \rho/\rho \sim 10^{-5}$. It was proposed that at the earlier epoch, if the density perturbations are larger than $\sim 0.3$, the primordial black holes (PBHs) would be formed \cite{1, 2}. These large perturbations cannot be achieved within the current popular theory which has predicted a scale invariant spectrum $P(k) \propto k^{-n}$, and the present observations give $n = 0.968 \pm 0.012$ \cite{3, 4}. So the large density perturbations can only be produced under some special conditions, such as the cosmological phase transitions or the feature at some scale of inflation potential \cite{5, 6}. In Ref. \cite{10}, the authors proposed that if the density perturbations during the radiation dominated epoch are less than 0.3 but larger than $10^{-3}$, one new kind of dark matter structures named ultracompact minihalos (UCMHs) would be formed. Because the density perturbations needed by the formation of UCMHs are smaller than PBHs, there are larger probability to form these new objects. After the formation of UCMHs, they will accrete the matter onto them through the radial infall. Due to the steep density profile and the early formation time of UCMHs, it is expected that compared with the standard dark matter halos, these compact objects would have some different and notable effect on the cosmological evolution. In Refs. \cite{11, 12}, the authors discussed the influence of the UCMHs on the CMB due to the dark matter annihilation within them and obtained the constraints on the abundance of UCMHs. The $\gamma$-ray flux from the UCMHs are also studied by several authors \cite{14, 15}. Besides the $\gamma$-ray, the electrons and positrons can also be produced from the UCMHs due to the dark matter annihilation. The synchrotron radiation will be produced due to the meeting between these high energy charged particles with the intergalactic magnetic fields. These radio signals would contribute to the cosmological background. For the cosmological radio background, the dominated contributions at frequencies above several GHz are from the cosmic microwave background (CMB). At the lower frequencies, the main contributions come from the extragalactic radio sources which have been detected by the current observations \cite{17, 18}. Recently, the radio flux excess with respect to the total contributions from the detected extra-galactic radio sources in the lower frequency region, $\nu \lesssim 10$GHz, was observed by ARCADE 2 \cite{19}. The final results are obtained by analyzing the data of the ARCADE-2 collaboration and older surveys at lower frequency observations \cite{20, 21}. These observations cannot be explained even when the unresolved astrophysical objects are included \cite{24, 25}. The authors of Refs. \cite{26, 27} found that the dark matter annihilation within the dark matter halos can fit the observations. On the other hand, these high energy electrons and positrons can inverse Compton scatter with the CMB photons into the X-ray or $\gamma$-ray band \cite{26, 28}. In this work, we studied the radio signals produced by the dark matter annihilation within the UCMHs and the corresponding X-ray and $\gamma$-ray signals. Using the observational data from Fermi, COMPTEL, CHANDRA and the ARCADE, the limits on the fraction of UCMHs are obtained.

This paper is organized as follows. The basic charac-
teristic of the UCMHs are discussed in Sec. II. In Sec. III we investigate the radio, X-ray and γ-ray signals from the UCMHs due to the dark matter annihilation and obtain the constraints on the fraction of UCMHs using these band observations. The conclusions and discussions are presented in Sec. IV.

II. THE FORMATION AND GROWTH OF UCMHS.

If the density perturbations during the radiation dominate epoch satisfy the condition \(10^{-3} \lesssim \delta \rho / \rho \lesssim 0.3\), one new kind of structures named ultracompact minihalos would be formed. In fact, the minimal value of the density perturbations depends on the time of horizon entry of the scale (for more detailed discussions one can see Ref. [29]). After the formation, the mass of UCMHs grows slowly because of the Meszaros effect until after the matter-radiation equality. The evolution of the mass has the form [12]

\[
M_{\text{UCMHs}}(z) = \delta m \left( \frac{1 + z_{\text{eq}}}{1 + z} \right),
\]

where \(\delta m\) is the mass within the scale of perturbations and it is different at different redshift. The density profile of UCMHs are obtained through the simulations [10], \(\rho \propto r^{-3.4}\). So, the specific form of the density profile can be written as

\[
\rho_{\text{UCMHs}}(r, z) = \frac{3f_x M_{\text{UCMHs}}(z)}{16\pi R_{\text{UCMHs}}(z)^2 r^2},
\]

where \(R_{\text{UCMHs}}(z) = 0.019 \left( \frac{1000}{z+1} \right) \left( \frac{M_{\text{UCMHs}}(z)}{M_\odot} \right)^{1/4}\) pc and \(f_x = \frac{\Omega_{\text{DM}}}{1 + (\pi t)^2} = 0.83\). The dark matter fraction. After \(z \sim 100\), the structure formation will dominate, so in this work we adopt the assumption that the UCMHs stop growing at \(z \sim 10\) [13, 15, 29]. On the other hand, since the dark matter annihilation will soften the central density of UCMHs, there is a maximal density \(\rho_{\text{max}}\) at time \(t\) for the formation time of UCMHs \(t_i\), \(\rho_{\text{max}}(r_{\text{min}}) = m_\chi / \langle \sigma v \rangle (t - t_i)\). Following the previous works [11, 10], we truncate the density profile at \(r = r_{\text{min}}\) and take the density within this radius as a constant, \(\rho(r < r_{\text{min}}) = \rho_{\text{max}}\).

III. THE MULTI-BAND SIGNALS FROM DARK MATTER ANNIHILATION WITHIN THE UCMHS.

As the essential component of the cosmos, dark matter has been confirmed by many observations. But its nature remains unknown. Now there are many dark matter models, and the much studied one is the weakly interacting massive particles (WIMPs) [30, 31]. One of the important models within the WIMP is the neutralino. According to the theory, these particles can annihilate into the standard particles, such as photon, electron and positron. The multi-band signals produced by these high energy particles has been studied as the clue of looking for the dark matter [32, 33]. Recently, the ARCADE 2 (Absolute Radiometer for Cosmology, Astrophysics and Diffuse Emission) released the results of the radio observations and found the excess at the lower frequency [19]. These results cannot be explained by the classical astrophysical sources. In Refs. [26, 27], the authors suggested that the classical dark matter halos due to the dark matter annihilation may be one kind of the sources for the excess. Besides the radio emission, the corresponding X-ray and γ-ray signals can also be produced through the dark matter annihilation [26, 28]. The authors of Ref. [28] found that only the dark matter models in which the mass is smaller than the dominating annihilation channel is the lepton channel can satisfy all band observations.

Compared with the standard dark matter halos, the density profile of UCMHs is steeper and the formation time is earlier. So it is expected that these objects can have significant contributions to the cosmological background [16]. In this work, we study whether the UCMHs can provide the sources for the radio excess. We also study whether the corresponding X-ray and γ-ray emission is consistent with other present observations, such as CHANDRA, COMPTEL and Fermi.

The signals from the UCMHs can be written as [26, 27, 34]:

\[
F_\nu = \frac{c \nu}{4\pi} \int \frac{e^{-\tau(z)}}{(1 + z) H(z)} \frac{dM}{dM_{\text{UCMHs}}} \times \mathcal{L}(E, z, M),
\]

where \(\tau\) is the optical depth and \(\mathcal{L}\) is the luminosity of UCMH. \(\mathcal{L}\) depends on the redshift and the mass of UCMHs,

\[
\mathcal{L} = \frac{\langle \sigma v \rangle}{2m_\chi^2} \times \int P_{\text{UCMHs}}(r, z) \, dr \times \int P(r, E, E') \times \left( \frac{1}{E} \int \frac{dN_e}{dE'} \, dE' \right),
\]

where \(dN_e / dE\) is the energy spectrum of the electron which can be obtained from the public code DarkSUSY [4]. \(\dot{E}\) is the energy loss rate \(\dot{E} = 3 \times 10^{-17} (1 + z)^2 \text{GeV s}^{-1} \) [34] and \(P\) is the emission power. For the synchrotron case and the inverse Compton process \(P\) can be written as

\[
P_{\text{syn}}(r, E, \nu) = \frac{\sqrt{3} \nu^3}{m_\gamma c^2} B(r) F(\nu / \nu_c),
\]

2 http://www.physto.se/ edsjo/darksusy/
\[ P_{IC}(r, E, E_\nu) = c \, E_\nu \int d\epsilon \, n_\gamma(\epsilon, r) \sigma(\epsilon, E_\nu, E), \]  

where \( \nu_c \equiv \frac{3 B(r)}{2 (m_e^2 + E^2)} B(r) E^2 \), \( m_e \) is the electron mass, and \( B(r) \) is the strength of the magnetic field, which is usually a function of the position. In this work, we consider the cosmological contributions from the UCMHs, so the dependence of the magnetic field on the position is not important \(^3\). After the formation of UCMHs and with the evolution of the universe, the UCMHs would be attracted into the classical dark matter halos due to the tidal force after the redshift \( z \sim 100 \). Therefore, the UCMHs would be distributed in some specific form, e.g., the NFW distribution. In this work, for simplicity, we assume that the UCMHs are distributed uniformly in the intergalactic space of the universe. The case that UCMHs are within the galaxy or cluster are also discussed in the next section. Therefore, we use the intergalactic magnetic field value and they have been determined by several observations \(^{33,36}\). However, there are much uncertainty about these results. In this work, we take the conservative value of the intergalactic magnetic field as \( B = 0.01 \mu G \) and our results can be applied to the case of other values of the magnetic field. For the mass function of UCMHs, \( dn/dM \), following the previous works \(^{11,16}\), we use the delta form \( dn/dM \sim \delta(M - M_{UCMH}) \). We also assume that UCMHs do not merge between them during their evolution. Therefore, we can define the fraction of UCMHs at present \( f_{UCMH} = \rho_{UCMH}/\rho_c \), where \( \rho_c \) is the critical density. Using these assumptions and definition, Eq. 7 can be rewrite as

\[ F_\nu = \frac{c \nu \, f_{UCMH} \rho_c}{4\pi \, M_{UCMH,0}} \int dz \frac{(1 + z)^2 e^{-\tau(z)}}{H(z)} \mathcal{L}(E, z, M)/(7) \]

From Eq. 8 it can be seen that the luminosity of UCMHs is proportional to \( \delta m \), \( \mathcal{L} \propto \int d^3p_{UCMH}(r, z) \mathcal{L}(E, z, M) \), so the final signals \( F_\nu \) in Eq. 9 is independent of \( \delta m \), \( F_\nu \propto \frac{1}{\delta m} \times \delta m \). In this work, we consider four annihilation channels: \( b\bar{b}, \tau^+\tau^-, \mu^+\mu^-, \) and \( e^+e^- \). The \( b\bar{b} \) and \( \tau^+\tau^- \) channel are the typical annihilation channels of the neutralino. The \( \mu^+\mu^- \) and \( e^+e^- \) channels are favored by the recent observations of positrons fraction: PAMELA \(^{37}\) and ATIC \(^{38}\). We fix the value of the dark matter mass and the annihilation cross section and adjust the fraction of the UCMHs to obtain the best fitting value for the radio data. In Figs. 1 and 2 we show the radio signals from the UCMHs due to the neutralino annihilation for the best fitting value of the fraction for the two typical channels. For the \( b\bar{b} \) channel, the best values of the UCMHs fraction are \( f = 5.0 \times 10^{-3} \) and \( 1.0 \times 10^{-2} \) for the dark matter mass 10 GeV and 100 GeV, respectively. For the \( \tau^+\tau^- \) channel, the fraction of UCMHs are \( f = 4.4 \times 10^{-2} \) and \( 5.9 \times 10^{-3} \), respectively. In Figs. 3 and 4 the results for lepton channels \( \mu^+\mu^- \) and \( e^+e^- \) are shown. The fraction of UCMHs are \( f = 2.5 \times 10^{-3} \), \( 3.9 \times 10^{-2} \) and \( f = 2.3 \times 10^{-4}, 2.2 \times 10^{-3} \) for \( m_{\chi} = 10 \) GeV and 100 GeV, respectively. For all these plots, we have set the dark matter annihilation cross section \( \langle \sigma v \rangle = 3 \times 10^{-26} \text{cm}^{-2}\text{s}^{-1} \).

\(^3\) We have taken the lower limit of integration of the density profile of UCMHs as \( r_{min} \) and \( \rho_{UCMH}(r_{min}) = m_\chi/\langle \sigma v \rangle \), so \( r_{min} \propto \delta m^{1/2} \). Therefore, the luminosity \( \mathcal{L} \) is proportional to \( \delta m^{-1/2} \times \delta m^{1/2} = \delta m \). The latter factor \( \delta m^{1/2} \) is from the other part of Eq. 2 except for \( r^{-9/4} \).
also inverse Compton scatter with the CMB photons to make them go into higher energy band, such as X-ray or soft \( \gamma \)-ray. On the other hand, the prompt emission can also contribute to the extragalactic \( \gamma \)-ray background \(34\). Although the dark matter model mentioned above can fit the radio data, these models must be consistent with other observations, such as X-ray and \( \gamma \)-ray \(26-28,34,40\). In Fig. 5 we show the signals of X-ray and \( \gamma \)-ray band from the UCMHs for the dark matter models which have been used to explain the radio excess. From this figure, we can see that the X-ray and \( \gamma \)-ray signals from those dark matter models are not consistent with the present observations: Fermi \(40\), COMPTEL \(33\) and CHANDRA \(41\). One of the important reasons is that the formation time of UCMHs is earlier, so the signals from the higher redshift can also have significant contribution to, for example, the soft \( \gamma \)-ray background. In order to be consistent with the observations, the constraints on the fraction of UCMHs can be obtained using these data. Firstly, in Fig. 6 we show the constraints on the UCMHs fraction from the radio excess data. On the other hand, the constraints on the UCMHs can be obtained from the CMB data. The product of the dark matter annihilation, such as photons, electrons and positrons, will interact with other particles existing in the universe. These effect will have impact on the ionization. The evolution of the electron fraction including the dark matter annihilation can be written as \(12\)

\[
\frac{dx_e}{dz} = \frac{1}{(1+z)H(z)}[R_s(z) - I_s(z) - I_{DM}(z)],
\]

where \(R_s\) and \(I_s\) are the standard recombination rate and ionization rate, respectively, and \(I_{DM}\) is the ionization rate from the dark matter annihilation. In this work, we consider the contributions from the UCMHs. The change of the evolution of the ionization can impact the power spectrum of CMB. So the parameters such as the dark matter mass and the annihilation cross section can be constrained by the CMB observations. In Refs. \(12,16\), the authors have investigated the impact of UCMHs on the CMB and obtained the constraints on the fraction of UCMHs using the WMAP7 data. In Fig. 6 we also show the constraints from WMAP7 data \(16\). In order to be consistent with the Fermi, COMPTEL and CHANDRA observations, the limits for the fraction of UCMHs from these data are also given in the figure. From this figure one can see that the strongest limits come from the X-ray observations and the constraints from the radio data are the weakest. \(4\)

\(4\) The results from the WMAP7 data are independent of the dark
FIG. 6. Constraints on the abundance of UCMHs from the ARCADE, Fermi, COMPTEL data and CHANDRA observations for different channels, $b\bar{b}, \tau^+\tau^-, \mu^+\mu^-$ and $e^+e^-$, used in this work. For all band observations, the 95% confidence regions and limits are shown. Here we have fixed the cross section $(\sigma v) = 3.0 \times 10^{-26} cm^3 s^{-1}$ for the dark matter annihilation. The constraints from the WMAP7 data are also shown. \[10\]

IV. DISCUSSION AND CONCLUSION

Due to the steep density profile and the early formation time of UCMHs, the dark matter annihilation within them will have potential significance as the astrophysical sources. The recent results of ARCADE 2 show that there are excess of radio signals for the frequency $\nu \lesssim 10$GHz. These results cannot be explained by the classical astrophysical objects even when the unresolved sources are also included. One of the possible explanations is the dark matter annihilation within the halos. In this work, we have studied the contributions of UCMHs to these observations. The dark matter particle mass considered here spread from 10GeV to 1TeV, and this range is favored by the direct or indirect observations. For the dark matter annihilation channels considered by us, $b\bar{b}$, $\tau^+\tau^-$, $\mu^+\mu^-$ and $e^+e^-$, the radio signals from the UCMHs can fit the ARCADE data for the different parameters. In this work, we use the radio data to obtain the constraints on the fraction of UCMHs. On the other hand, the high energy electrons and positrons can inverse Compton scatter with the background photons, such as CMB photons, to make them go into the X-ray or $\gamma$-ray band. We studies these signals from the UCMHs using the models which can fit the ARCADE data. We found that the X-ray or $\gamma$-ray signals exceed the present observations, such as CHANDRA, COMPTEL and Fermi data. Using these data, we also obtained the limits on the fraction of UCMHs. Compared with the results from the radio data, the constraints are stronger, especially for the X-ray observations, and the strongest limit is $f_{\text{UCMHs}} \sim 10^{-6}$ for the dark matter mass $m_\chi = 10$GeV. In this work, we do not consider the standard dark matter halos. In Refs. [26,28], their contributions have been discussed in detail. The authors of [28] found that in order to fit the radio data and be consistent with the $\gamma$-ray observations, only those dark matter models which annihilate into the $\mu^+\mu^-$ or $e^+e^-$ and the mass is in the range of $5 \sim 50$GeV can satisfy all band observations. Moreover, considering the uncertainties of the magnetic field and the density profile of halos, the dark matter annihilation cross section is in the range, $(\sigma v) \sim (0.4 - 30) \times 10^{-26} cm^3 s^{-1}$. So, if the standard dark matter halos are included, the constraints on the fraction of UCMHs obtained in this work would be changed and the details depend on the parameters of dark matter, the density profile of halos and the magnetic field. On the other hand, we have considered the homogeneous distribution of UCMHs and used the intergalactic field. The value of the magnetic field is smaller than the case of galaxy. If the UCMHs are present in the galaxy and the cluster, the constraints on the fraction of UCMHs will become stronger.

In summary, we have studied the radio, X-ray and $\gamma$-ray signals from the UCMHs due to the dark matter annihilation. We found that under the reasonable assumptions of the related parameters, the UCMHs which fit the radio excess observations are not consistent with the other band data. The limits on the fraction of UCMHs are obtained from all band observations, ARCADE 2, COMPTEL, CHANDRA and Fermi data and the strongest constraints come from the X-ray data.

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