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SECONDARY ELECTRONS IN CLUSTERS OF GALAXIES AND GALAXIES

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ABSTRACT

We investigate the role of secondary electrons in galaxy clusters and in ultra-luminous infrared galaxies (ULIGs). The radio emission in galaxy clusters and ULIGs is believed to be produced by the synchrotron radiation of relativistic electrons. Nonetheless, the sources of these relativistic electrons are still unclear. Relativistic secondary electrons can be produced from the hadronic interactions of cosmic-ray nuclei with the intra-cluster media (ICM) of galaxy clusters and the dense molecular clouds of ULIGs. We estimate the contribution of the secondary electrons in galaxy clusters and ULIGs by comparing observational results with theoretical calculations for the radio emission in these sources. We find that the radio halos of galaxy clusters can not be produced from the secondary electrons; on the other hand, at least for some ULIGs, the radio emission can be dominated by the synchrotron emission of the secondary electrons.

Key words : cosmic rays – clusters of galaxies

I. INTRODUCTION

It is difficult to observe the cosmic-ray hadrons for extragalactic sources directly. The only way to investigate the cosmic-ray hadrons of extragalactic sources is via some indirect tracers of the cosmic-ray hadrons, such as the emission of high-energy gamma rays and neutrinos resulted from the interactions of the cosmic-ray protons and the intra-cluster (IGM) or inter-stellar (ISM) gas. If the gas contains magnetic fields, it is then also possible to investigate the cosmic-ray hadrons via the radio emission produced by the synchrotron radiation of relativistic secondary electrons, which are resulted from the charge pion decays that are generated in the inelastic collisions of the cosmic-ray hadrons with the IGM/ISM gas.

The extragalactic sources that most likely to show observable synchrotron emission of secondary electrons should have high ISM/IGM density and high cosmic-ray proton intensity. Both clusters of galaxies and ultra-luminous infrared galaxies (ULIGs) are believed to be have luminous cosmic rays and thus sttrong secondary electron sources. In this paper we investigate the observable properties of the secondary electrons in these two sources.

(a) Clusters of Galaxies

For clusters of galaxies, cosmic-rays might be produced through the merging shocks during the formation of the clusters. Cluster merging is a very violent event and releases a large amount of energy ($\sim 10^{64}$ ergs); this leads cluster mergers to be a very favorable mechanism for the production of the relativistic particles. Besides, radio galaxies, starbursts, and active galactic nuclei (AGNs) in the clusters can also contribute significant cosmic rays to the ICM of the clusters. It has been recognized that the diffusion time of cosmic-ray protons is comparable with the age of the universe. Since the radiative losses of cosmic-ray hadrons are negligible, cosmic-ray protons are accumulated and confined within galaxy clusters for the lifetimes of the clusters (*i.e.,* Völk *et al.* 1996 ;Berezinsky, Blasi, & Ptuskin 1997).

Diffuse radio emission are usually found in rich galaxy clusters with high IGM temperatures. These radio sources, which usually possess large sizes and steep spectra, are called radio halos if they permeate the cluster centers and radio relics if they are located in cluster peripheral regions. The diffuse radio emission of galaxy clusters is believed to be produced by the synchrotron radiation of relativistic electrons. Since relativistic electrons lose energy on the time scale of order $\sim 10^7 - 10^8$ years because of inverse Compton and synchrotron losses, without re-acceleration or regeneration radio halos in galaxy clusters might be just transient features. On the other hand, if radio halos are formed from the secondary electrons, their lifetimes would be comparable with the cosmological time because of the continuum re-generation of the relativistic electrons following collisions between the cosmic-ray protons and the ICM gas. These significantly different time scales could have discernible effects on the number distribution of the radio halos and thus could discriminate on their origins.

(b) Ultra-Luminous Infrared Galaxies

ULIGs are galaxies with far infrared luminosities $L_{FIR} \geq 10^{12} L_{\odot}$. These galaxies radiate most of their energy in the far infrared and are the most luminous

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galaxies in the local universe (Sanders & Mirabel 1996). Most of these galaxies also possess a huge amount of molecular gas, which is usually concentrated in a small central region (*leq* 1kpc) and has average density comparable with that of Galactic molecular clouds. The energy source of ULIGs are generally considered to be from starbursts triggered by the merging of gas-rich galaxies.

The radio and far infrared luminosities of ULIGs were found to have a correlation similar to that for galaxies with lower luminosities. The high luminosities of ULIGs indicate that ULIGs must be strong radio emitters. The major part of the radio emission from the ULIGs are believed to be synchrotron emission from relativistic electrons in a weak magnetic field. The origin of the relativistic electrons were generally believed to be accelerated in the galaxy interaction or resulted from the supernova events following the high star formation activities in the ULIRGs. A small fraction of the radio emission might be bremsstrahlung emission from H II regions. We note that in some cases where the radio emission is resolved, the radio emission is found to be spatially correlated with the CO emission (*e.g.,* Hwang & Chiou 2004).

Secondary relativistic electrons can be produced through the hadronic interactions of cosmic-ray nuclei with the interstellar medium. In the solar neighborhood of the Milky Way, most of the relativistic electrons are primary. However, we note that the production rate of the secondary electrons is proportional to the cosmic-ray fluxes and the density of the ambient gas. Cosmic-ray fluxes are expected to be high in galaxies of high star formation rates because of high supernova rates. The high molecular gas density and the enhanced star formation rates in ULIGs suggest that the production rate of secondary relativistic electrons is greatly enhanced in ULIGs and might be the dominant sources of relativistic electrons.

II. RESULTS AND DISCUSSION

(a) Clusters of Galaxies

Kuo, Hwang, & Ip (2004) has estimated the fractional distribution of radio halos by calculating the formation rates of radio halos from the hierarchical model. The calculated results are compared with the observations and are shown in Fig 1. From observations, about 28% ∼ 38% of clusters with $L_X > 10^{45}$ erg s^{-1} possess radio halos (Giovannini *et al.* 1999). In contrast, the theoretical calculation show that the percentage of clusters possessing radio halos should be greater than 70% if the life time of the halo is comparable with the Hubble time scale. In other words, if the secondary electron model was applicable, most of these massive clusters should possess radio halos. According to these results, the secondary electrons do not seem to be the dominant origin of the radio halos. On the other hand, if radio halos were transient phenomena associated with a single acceleration event, such as a major merger shock, they would have lifetimes ∼ 0.1 Gyr. Because of the short lifetimes of the sources, radio halos would be hardly observable even in the massive clusters. The observed percentage is thus too high to explain in the hierarchical clustering formation model. The only viable models for the radio halos are those of primary electrons with significant re-acceleration (*e.g.,* Kuo, Hwang, & Ip 2003).

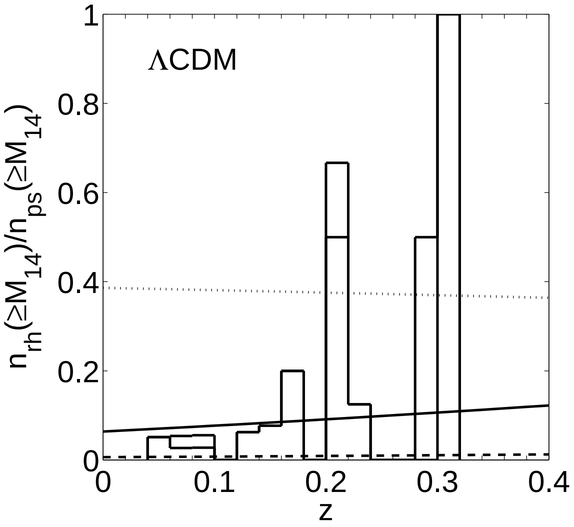

Fig. 1.— Distributions of the total number density ratios of radio halos to galaxy clusters. The lifetimes for the radio halos are: 0.1 Gyr (*dashed curves*), 1 Gyr (*solid curves*), and the cosmological time (*dotted curves*). The histograms represent the observational results of Giovannini *et al.* (1999) (Adapted from Kuo, Hwang, & IP 2004).

We can also estimate the energy distribution of secondary electrons in a galaxy cluster by considering complete loss and generation mechanisms. Here we take the Coma cluster as an example. Fig. 2 & Fig. 3 show the results for such estimates with different magnetic fields assuming a steady state condition. The generation mechanisms for the secondary electrons considered here include the charged pion decays and the knock-on electrons; the energy loss mechanisms include the synchrotron radiation, the inverse Compton scattering of the cosmic microwave background photons, the ionization, and the bremsstrahlung of the secondary electrons.

These results indicate that the cosmic-ray energy density in the Coma cluster might be no more than 1% of the thermal energy density if the magnetic field is about 5μG. The allowed cosmic-ray energy density can be slightly more if the magnetic field is around 0.4μG. In any case, the EUV electrons are difficult to explain by a secondary model in a stead state .

The low energy secondary electrons are dominated by the knock-on electrons, which are resulted from the scattering of the cosmic-ray protons with the thermal ICM electrons. We note that these knock-on electrons might contribute hard X-ray and soft gamma-ray emis-

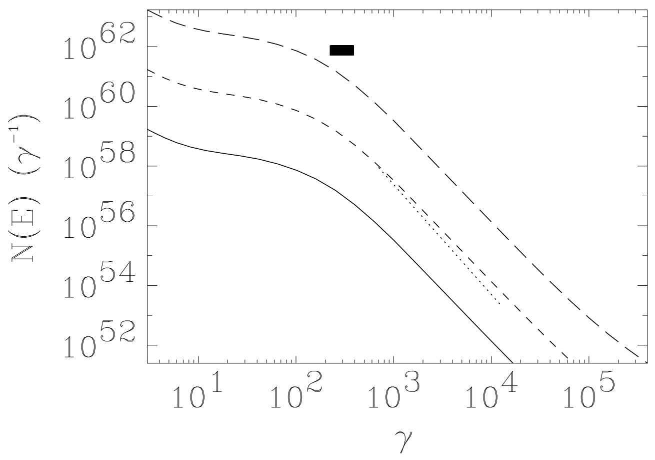

Fig. 2.— Energy distributions of secondary electrons in Coma cluster with the average magnetic field assumed to 5μG. The energy density of hadron cosmic-rays are assume to be : 100% (*long dashed curves*), 1% (*short dashed curves*), and 0.01% (*solid curves*) of the thermal ICM energy. The dotted curve represent the synchrotron-radiating electrons for the observed radio emission. The filled solid square represents the observed EUV electrons in an IC/3K EUV model (*e.g.,* Hwang 1997).

sion through their non-thermal bremsstrahlung emission.

(b) ULIGs

To study the secondary electrons in ULIGs, we have selected a sample of ULIGs from Solomon *et al.* 1997. The sample contains results of CO interferometric observations for 37 ULIGs in the red-shift range of $z = 0.03 - 0.27$. Since the average ISM densities and thus the magnetic fields of these galaxies are very large, it is reasonable to assume a steady state for the secondary electrons generated from the interaction of the cosmic-ray hadrons and the molecular clouds of these galaxies.

We don't know the cosmic-ray energy densities in these ULIGs. However, since far infrared luminosity is strongly related to star formation activity, it seems reasonable to assume that the cosmic-ray density is proportional to the far infrared luminosity of the galaxy. With this assumption, we can derive the magnetic fields in all these ULIGs by comparing their observed radio emission with theoretical calculations for a secondary electron model.

Our results show that more than 50% of the ULIGs have a derived magnetic field less than 100 μG. We note that the observed average ISM number densities of these ULIGs are around 1000 cm^{-3}, which similar to the average density of molecular clouds of our Milky Way. Since the magnetic field is expected to proportional to the density, $B \propto \rho^{2/3}$, the derived magnetic fields thus seem to be reasonable values for the magnetic fields in the ISM of these ULIGs. In other words, secondary electrons must be the dominant source for their radio emission for these ULIGs.

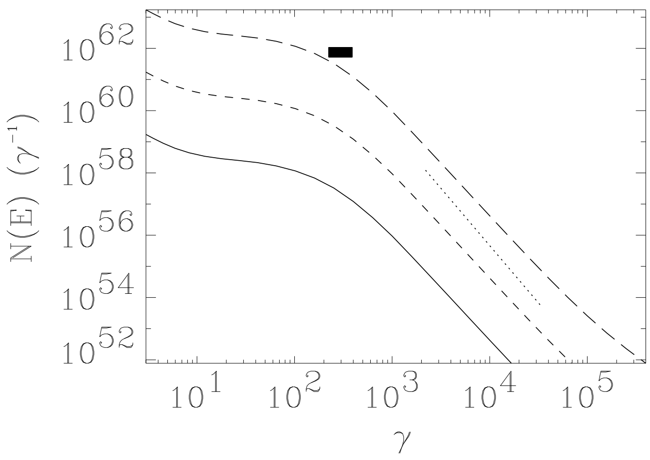

Fig. 3.— Same as Fig 2 except that the average magnetic field is assumed to be 0.4μG.

On the other hand, for those ULIGs with obvious AGN activities, our calculation have derived much higher magnetic field strengths (>400μG). This is consistent with the fact that the radio emission in those AGN-like ULIGs are mainly powered by AGNs. Our results thus indicate that the origins of the observed non-thermal radio emission from normal galaxies, starburst ULIGs, and AGN-like ULIGs are all different.

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