次級電子在極明亮紅外星系中所扮演的角色

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摘要

我們研究的重點主要是—探究次級電子（secondary electrons）在極明亮紅外星系裡所扮演的角色。一般相信，極明亮紅外星系所觀測到的1.4GHz無線電輻射，主要是來自於相對論性電子所產生的同步輻射。然而，我們對於到底是何種機制會產生如此高速的相對論性電子，則是一無所知。由觀測顯示，大多數的極明亮紅外星系，不但擁有很高的恆星誕生率，同時也有相較於一般正常星系更多的分子雲含量。在另一方面，由於次級電子的產生率，和宇宙射線流以及物質的密度有著正比的關係，因此我們認爲在極明亮紅外星系中，由這些次級電子所產生的無線電輻射量必定是不可忽略的。我們所考慮的是一個由宇宙射線質子和分子雲質子碰撞後，進而產生次級電子的穩態方程式。我們藉由理論模型和觀測資料的比對後，發現在某些極明亮紅外星系裡，這些次級電子對於在1.4GHz所觀測到的無線電輻射量，具有顯著性的貢獻！

Secondary Electrons on Ultraluminous Infrared Galaxies

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Abstract

We investigate the role of secondary electrons in ultraluminous infrared galaxies (ULIGs). The radio emission in ULIGs is believed to be produced by synchrotron radiation of relativistic electrons. Nonetheless, the sources of these relativistic electrons are still unclear. Most of the ULIGs usually have enhanced star formation rates and also possess a huge of amount of molecular clouds, which are usually concentrated in a small central region (≤ 1 kpc). Since the production rates of the secondary electrons are proportional to the cosmic ray fluxes and the density of the ambient gas, the radio emission of the secondary electrons in ULIGs might be important. We assume a steady-state model for the secondary electrons generated from the interaction of the cosmic-ray hadrons with dense molecular clouds in ULIGs. We estimate the contribution of the secondary electrons in ULIGs by comparing observational results with theoretical calculations for the radio emission in these sources. We find that, for some ULIGs, radio contribution from synchrotron radiation of secondary electrons is significant.

關鍵字（Key words）：星系（galaxy）、宇宙射線（cosmic rays）、明亮紅外星系（ULIGs）

1. Introduction

1.1. Ultraluminous Infrared Galaxies

Ultraluminous infrared galaxies (ULIGs) are known to emit the bulk of their energy in the infrared, and their infrared luminosity ($L \geq 10^{12} L_{\odot}$) are equivalent to the bolometric luminosities of optically selected quasars. One of the most basic issues of the ULIGs is the energy source powering the enormous amount of their infrared radiation. Spectroscopic studies in the optical, near-infrared and mid-infrared suggest that about 70 percent and 30 percent of these galaxies are powered by starburst activities and active galactic nuclei (AGNs), respectively (Genzel et al. 1998; Veilleux et al. 1999). The huge infrared luminosity of the ULIGs suggests that they contain a large reservoir of molecular gas to provide fuel for the star formation and AGN activities. Extensive searches for CO emission have indeed shown that most of the ULIGs possess a huge amount of molecular clouds and there is a trend of increasing molecular gas content with the far-infrared emission. Moreover, Gao & Solomon (2004) also show that the density of molecular clouds is much higher than in ordinary giant molecular clouds by HCN observation.

1.2. Observational Properties of the Molecular Clouds

On the other hand, the radio images of normal galaxies are distributed about 30kpc (Mayya & Rengarajan 1997), which show more diffuse than that of the molecular clouds. It is different from that in ULIGs. Recent interferometric observations of nearby ULIGs (Downes & Solomon 1998) have determined that molecular clouds are concentrated in a circumnuclear disk of typically 1 kpc, which is the same size with their radio images. This leads to the suggestion that mechanism causing the radio emission of the ULIGs might be different from that in normal galaxies.

1.3. Non-thermal Radio Emission

On the other hand, there is a tight correlation between far-infrared (FIR) and non-thermal radio luminosity, which has been well established over 3-4 order of magnitude from normal galaxies to ULIGs (Dickey & Salpeter 1984; De Jong et al. 1985; Price & Duric 1992). As FIR radiation is due to dust heating by young massive stars (see Volk & Xu 1994), FIR provides a direct measurement of star formation rates in galaxies. Thus the FIR/radio correlation implies that non-thermal radio emission should be related to massive star formation and to their possible evolution towards supernova stage.

However, the problem of explaining the origin of the non-thermal radio emission of galaxies has been still unclear. It is widely accepted that the observed non-thermal radio emission of galaxies are produced by relativistic electrons directly from supernovae explosion. Therefore, most recent studies have focused on primary electrons (Gavazzi et al. 1986; Cox et al. 1988; Xu et al. 1994; Bell et al. 2003), but little is known to the contribution of the secondary electrons produced from the hadrons interactions of cosmic ray nuclei with the dense molecular clouds of galaxies. Such collision gives rise to charged pions, which will soon decay to μ and finally to the secondary electrons.

1.4. The Importance of the Secondary Electrons

Since the production rate of secondary electrons is proportional to the cosmic-ray fluxes and the density of the ambient gas, and even the magnetic field in dense clouds may be enhanced over the mean interstellar field, one can expect that radio emission of the secondary electrons in ULIGs which usually have a large fraction of higher density of molecular clouds (Solomon et al. 1997; Gao & Solomon 2004) and higher star formation rate might be important.

In this paper, we take a different approach, investigating the radio contribution from the secondary electrons in ULIGs. The paper is structured as follows. In section 2 we develop our model and calculate the synchrotron radiation of the secondary electrons. In section 3 we show the criteria of our comparison sample, and make a comparison between observational results and our theoretical calculations for the radio emission in these sources. In section 4 we discuss the origin of radio emission in ULIGs and their FIR/radio correlation. In section 5 we make a conclusion.

2. Steady-State Model

We assume a steady-state model for the secondary electrons with uniform cloud of density n and magnetic field B that is exposed to an isotropic and homogeneous flux of cosmic rays. Let N(γ)dγ be the total number of electrons in ULIGs with energies in the range γ to γ+dγ. We also assume that cosmic-ray electrons and ions are trapped within the galaxies and cannot escape. Then the equation for the evolution of electron population is

$$d[b(\gamma)N(\gamma)]/d\gamma = -Q(\gamma) \qquad (1)$$

where b(γ) represent the cooling functions by different processes, and Q(γ) gives the total production rate of new cosmic-ray electrons in the energy range γ to γ+dγ.

It is important to note that there is an assumption that the confinement time is long compared with the time scale for the electrons to lose their energy. This could be allowed due to the enhanced magnetic field in the molecular clouds. Secondary electrons produced within the molecular clouds will not escape before losing all of their energy.

2.1. Production Rate of Secondary Electrons

This section is based on a formalism developed by (Marscher & Brown 1978). The steady-state cosmic ray spectrum is governed by injection of secondaries and cooling processes. The interaction of fast cosmic rays with atoms in molecular clouds leads to production of energetic secondary electrons in these clouds principally by three processes: knock-on collisions, neutron decay, and pion-decay reactions. If we use the approximate form of the locally measured energy spectrum of cosmic ray protons over the 1-20 GeV range (Brunstein & Cline 1966; Fisk 1976),

$$dJ_p/dE_p = 6.41\times10^{-5}E_p^{-2.5}\ cm^{-2}s^{-1}sr^{-1}erg^{-1} \qquad (2)$$

we use the following approximate knock-on production rate (Marscher & Brown 1978):

$Q(E) \approx 1.6 \times 10^{-34}\ \eta n E^{-2.76}$ (3)

where E is the electron energy and in unit of erg. η represents the ratio of the energy density of the cosmic ray between those ULIGs and the Milky Way, and it is proportional to star formation activities. n is the number density of the molecular cloud within the galaxies. In other words, the production rate of the secondary electrons will be enhanced with increasing cosmic ray flux and the number density within the molecular clouds.

Energetic secondary electrons may also result from the β-decay of neutrons created as secondaries following cosmic ray interactions with dense clouds. Calculation of the energy spectrum of the β-decay electrons must be carried out as a two-step process since it depends both on the energy spectrum of electrons relative to the rest frame of the parent neutrons and on the energy spectrum of neutrons relative to the observer. The observed neutron energy spectrum also depends on the spectrum of neutrons relative to the rest frame of the cosmic ray interaction and on the spectrum of cosmic rays relative to the observer. We use the production rate for neutron-decay electrons approximated by (Marscher & Brown 1978)

$Q(E) \approx 31\sigma(mc^2)^{1.5}\eta n E^{-2.5}$ (4)

Finally, the production mechanism for secondary electrons resulting from charged-pion decays can be approximated to within 5 percent by the following expressions

$Q(E) \approx 7.2 \times 10^{-31}\ \eta n K(E) E^{-2.44},$

$for\ E > 8.0 \times 10^{-4} erg$ (5)

where $K(E)=1.1+0.05\log E_{GeV}$ accounts for various other decay modes such as kaon decay which are capable of producing energetic secondary electrons (Orth & Buffington 1976).

2.2. Cooling Function

The energy loss function consisting of hydrogen and helium with a total number abundance ratio of 10:1 for ionization is given by (Schlickeiser 2002)

$b(\gamma)=d\gamma/dt=(2.7c\sigma_T[6.85+ln\gamma][n_{HI}+2n_{H2}])s^{-1}$ (6)

where n is the number density in the molecular cloud, and σ_T is the Thomson cross section. It is also the most important energy loss function at lower energies.

The expression for the loss rate due to synchrotron is given by

$b(\gamma)=d\gamma/dt=(4\sigma_T c\gamma^2\beta^2 U_B/3mc^2)\ s^{-1}$ (7)

where U_B is the magnetic energy density and it affects high energy electrons.

The energy loss function for inverse Compton is given by

$b(\gamma) = d\gamma/dt = (4c\sigma_T\ \omega\beta^2\gamma^2/3mc^2)\ s^{-1}$ (8)

where ω is the photon energy density. Obviously, the loss rates for inverse Compton and for synchrotron losses vary in the same manner with γ^2.

The relativistic electrons will also lose energy by bremsstrahlung, which is given approximately by

$b(\gamma)=d\gamma/dt=(3.9\alpha c\sigma_T\ \gamma\varphi[n_{HI}+2n_{H2}]/8\pi)s^{-1}$ (9)

where σ_T is the Thomson cross section and α=1/137.037 is the fine structure constant. φ is energy-dependent scattering function which depend on the properties of scattering system. Given in Table 1 are the scattering function φ_1 and φ_2 when the target is a hydrogen atom or a helium atom as a function of the parameter

$\Delta = (4\alpha\gamma)^{-1}$ (10)

In contrast to the synchrotron and inverse Compton losses, the bremsstrahlung energy loss rate is linearly proportional to the relativistic electron energy E.

It is clear from the expression that the ionization losses dominate for sufficiently small energies or for higher density. Bremsstrahlung losses are likely to be dominant when the density is very high. Similarly, synchrotron losses are dominant in the molecular cloud with much stronger magnetic field than in the ISM.

Table 1. Scattering function φ_1 and φ_2 for the hydrogen atom and helium atom. (Schlickeiser 2002)

$(4\alpha\gamma)^{-1}$	$H(\varphi_1)$	$H(\varphi_2)$	$He(\varphi_1)$	$He(\varphi_2)$
0	45.79	44.46	134.6	131.4
0.01	45.43	44.38	133.85	130.51
0.02	45.09	44.24	133.11	130.33
0.05	44.11	43.65	130.86	129.26
0.1	42.64	42.49	127.17	126.76
0.2	40.16	40.19	120.35	120.80
0.5	34.97	34.93	104.60	105.21
1	29.97	29.78	89.94	89.46
2	24.73	24.34	74.19	73.03
5	18.09	17.28	54.26	51.84
10	13.65	12.41	40.94	37.24

2.3. Synchrotron Emission of Secondary Electron

In general, synchrotron power per unit frequency is obtained by averaging over all orientations of the magnetic field and all pitch angles for electrons (Sarazin 1999)

$$L_v = (1.732 e^3 B / m_e c^2) \int N(\gamma) R[x(\gamma)] d\gamma \quad (11)$$

where N(γ) is the spectrum of secondary electrons resulted from a steady-state model. The function R(γ) is defined as (Ghisellini, Guilbert & Svensson 1998)

$$R(x) \equiv 2x^2 (K_{4/3}(x) K_{1/3}(x) - 0.6[(K_{4/3}(x))^2 - (K_{1/3}(x))^2]) \quad (12)$$

where K is the modified Bessel function. The normalized frequency variable x is

$$x \equiv \nu / 3\gamma^2 \nu_c \quad (13)$$

where ν_c is the cyclotron frequency

$$\nu_c \equiv eB / 2\pi m_e c \quad (14)$$

3. Comparison with Observation

Our comparison samples of the ULIRGs are selected from Solomon et al. (1997), of which contains 37 infrared-luminous galaxies in the redshift range z=0.03-0.27. They have been previously observed in CO by several groups. The number density, masses of molecular clouds and FIR luminosity have been all determined (see Table 2). The radio data for those ULIRGs were obtained from the completed NRAO VLA Sky Survey (NVSS) (Condon et al. 1998).

3.1. Magnetic Field

Magnetic field could be also an important parameter in determining the radio powers of the ULIGs. It is very difficult and complicated to determine this parameter. For cluster of galaxies, we can use Faraday rotation measurement to determine the magnetic field. But for galaxies, the size of which are too small, so it is not easy to determine the magnetic field strength, not to mention the magnetic field of the molecular clouds within the galaxies. Therefore, we compare the parameters of the observational data made by Solomon et al.(1997) with our secondary electrons model and then the magnetic field could be determined (See Table 2). We assume that the FIR luminosity is all from star formation activities, because observation data shows that there

Table 2. Derived Magnetic Field From Pure Secondary Electron Model

Source Name	Radio Power Field log(erg/s/Hz)	FIR Power log($L_{FIR}/L_{\odot}$)	Molecular Mass log($M/M_{\odot}$)	Density (cm^{-3})	Magnetic (μG)
00057+4021	29.47	11.5	10.23	2850	310
00188-0856	30.74	12.18	10.49	1932	830
00262+4251	30.72	12.00	10.46	1023	>2500
I Zw 1	29.77	11.47	10.43	3060	500
Mrk 1014	30.66	12.33	10.60	576	688
02483+4302	30.02	11.62	10.11	1352	650
03158+4227	30.68	12.44	10.51	613	613
03521+0028	30.48	12.35	10.63	304	663
04232+1436	30.56	11.88	10.61	1544	1160
VII Zw 31	30.38	11.81	10.73	265	>1800
07598+6508	30.24	12.13	10.72	893	437
08030+5243	29.33	11.88	10.61	1653	705
08572+3915	30.50	12	09.88	7862	642
09320+6134	30.70	11.84	10.32	1570	2800
10035+4852	30.36	11.83	10.51	646	1380
10190+1322	30.31	11.88	10.58	1316	710
10495+4424	30.56	12.05	10.58	846	1000
10565+2448	30.56	11.89	10.41	1000	746
11506+1331	30.64	12.17	10.53	772	960
Mrk 231	31.03	12.29	10.54	702	>2100
13106-0922	29.32	12.28	10.63	410	90
Arp 193	29.04	11.50	10.26	3156	171
Mrk 273	30.58	12.03	10.36	1284	918
13442+2321	29	12.07	10.38	518	77
14070+0525	29.83	12.58	10.63	648	119
15030+4835	29.57	12.23	10.76	404	139
Arp 220	30.25	12.06	10.51	3549	431
16090-0139	30.87	12.36	10.75	477	>2500
16334+4630	29.81	12.26	10.43	673	183
NGC6240	30.74	11.66	10.57	1320	>2500
17208-0014	30.56	12.33	10.51	1602	485
18368+3549	30.74	12.08	10.59	775	>2500
19297-0406	30.62	12.26	10.63	680	775
19458+0944	29.45	12.20	10.74	633	119
20087-0308	30.11	12.27	10.87	824	285
22542+0833	29.45	12.20	10.45	529	120
23365+3604	30.36	12.00	10.59	777	735

is a tight linear correlation between FIR luminosity and dense molecular clouds related to star formation (Gao & Solomon 2004). Therefore, it is reasonable that cosmic ray energy density is proportional to the FIR luminosity per unit volume. Then we can estimate the cosmic ray ratio between our Galaxy and other galaxies. With all the parameters mentioned accordingly, we can estimate the maximum magnetic field of the whole molecular clouds.

3.2. Constraint On Source Of Radio Emission

By comparison with the isotropic contraction theory of molecular cloud ($B \propto (\rho/\rho_0)^{2/3}$), of which ρ_0 is 300/cm^3, the mean number density of molecular cloud of the Galaxy (Tomoharu Oka & Tetsuo Hasegawa et al. 1998; Solomon 1990; Gao & Solomon 2004), we identify two types of ULIGs according to the derived magnetic field. For galaxies with the same order of magnitude of the theoretical magnetic field in the mean molecular clouds, that means the radio contribution from secondary electrons is significant. But for galaxies with the derived magnetic field which are higher than the theoretical magnetic field, we suggest that the mechanism causing the observed radio emission in those ULIGs might be possibly from other mechanisms such as AGN activities or their radio emission might also be from the primary electrons (See Table 3).

3.3. Result

Accordingly, our results show that the contribution from radio emission of the secondary electrons is significant for some ULIGs, and there are two types of ULIGs, which are classified by their derived magnetic field strength as compared with the theoretical magnetic field. One can be explained by our secondary electron model, and the other cannot. This also implies that radio emission of the secondary electrons might be different in different types of ULIGs.

4. DISCUSSION

4.1. The FIR/Radio Correlation

In order to get more insight properties, we also investigate the FIR/Radio correlation of our samples. Fig 1 represents the FIR/Radio correlation of the ULIGs whose radio contribution from secondary electrons is significant, and the linear correlation coefficient is R=0.34 with p-value equal to 0.41. Fig 2 shows that the FIR/radio correlation of the ULIGs whose radio contribution from secondary electrons is not significant, and the linear correlation coefficient is R=0.06 with p-value equal to 0.71.Meanwhile, we also identify 6 ULIGs powered by AGN activities from NED in our sample whose radio

Table 3. Comparison between the derived and theoretical magnetic field

Source Name	Derived Magnetic Field (μG)	Theoretical B$\propto(\rho/\rho_0)^{2/3}$ (μG)	Note (secondary electron model)
00057+4021	310	136	*
00188-0856	830	104	*
00262+4251	>2500	68	
I Zw 1	500	142	*
Mrk 1014	688	46	
02483+4302	650	82	
03158+4227	613	48	
03521+0028	663	30	
04232+1436	1160	90	
VII Zw 31	>1800	28	
07598+6508	437	62	
08030+5243	705	94	
08572+3915	642	268	*
09320+6134	2800	91	
10035+4852	1380	50	
10190+1322	710	81	
10495+4424	1000	60	
10565+2448	746	67	
11506+1331	960	57	
Mrk 231	>2100	53	
13106-0922	90	37	
Arp 193	171	145	*
Mrk 273	918	79	
13442+2321	77	43	*
14070+0525	119	50	
15030+4835	139	37	
Arp 220	431	157	*
16090-0139	>2500	41	
16334+4630	183	52	
NGC6240	>2500	81	
17208-0014	485	92	
18368+3549	>2500	57	
19297-0406	775	52	
19458+0944	119	49	
20087-0308	285	59	
22542+0833	120	44	
23365+3604	735	57	

contribution from secondary electrons is not significant. This leads to suggestion that some of those ULIGs might be powered by AGN activities. But none are identified to be powered by AGN for ULIGs whose radio contribution from secondary electrons is significant.

4.2. Magnetic Field Criterion

Since it is still an open question to the global magnetic field of the molecular clouds within the 1 kpc of the galaxies, the only way we can

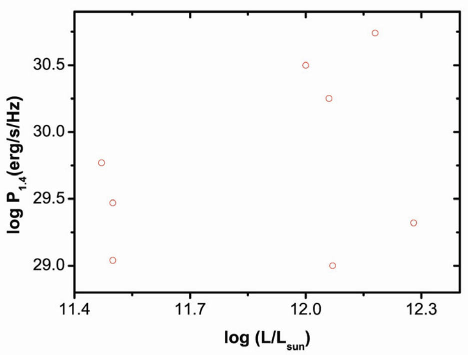

Fig. 1.—Correlation between radio emission and FIR luminosity. The linear correlation coefficient for ULIGs which can be explained by secondary electron model is R=0.34 with p=0.41

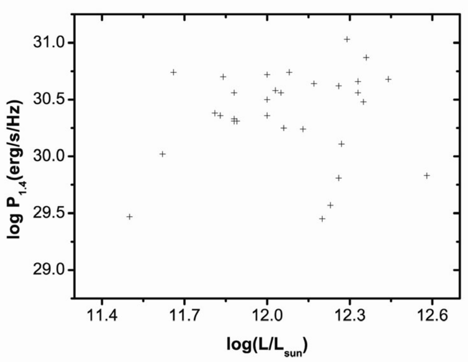

Fig. 2.—Correlation between radio emission and FIR luminosity. The linear correlation coefficient R=0.06 with p=0.71 for ULIGs which cannot be explained by our secondary electron model, suggesting that AGN activities might be the mechanisms.

compare is the theoretical magnetic field of the molecular cloud, which shows the relation between magnetic field and density of the molecular clouds, $B \propto (\rho/\rho_0)^{2/3}$.

Although observation reveals that the relation between magnetic fields and density of molecular clouds are in favor of the relation $B \propto (\rho/\rho_0)^{1/2}$ (Basu 2000). But this is only due to the individual dense clouds among the galaxies. What we consider here is the global magnetic field of the whole molecular clouds within 1 kpc of the ULIGs, instead of the individual ones. Thus, we don't have to take the magnetic energy loss into account, which might not be neglected in individual clouds. Therefore, it should be suitable to take this as our comparison criterion.

It is important to note that the magnetic field we derived are the upper limit, because what we consider here is only the contribution of radio emission from secondary electrons generated from the interaction of the cosmic-ray hadrons with dense molecular clouds. We didn't take into account the contribution from other sources, such as primary electrons directly from radio sources in ULIGs.

4.3. Proton Spectrum Assumption

In order to calculate the production rates of the secondary electrons within the ULIGs, we make an assumption that all ULIGs have the same proton spectrum as the Milky Way galaxy. It is generally believed that the cosmic ray protons are accelerated at the shock wave produced through the supernovae explosion in normal galaxies. Thus, the mechanisms in ULIGs should also be the same as long as their power sources are related to star formation activities. The only difference is the fact that there are higher star formation activities in ULIGs, which will produce more cosmic rays.

It seems reasonable to assume that cosmic rays are produced at a rate proportional to the supernovae rate, or to the current star formation. Supernovae explosion have been the basic sources of cosmic rays in the Galaxy. Therefore, cosmic ray flux will increase with the increasing star formation activities. In ULIGs, we will expect more cosmic rays than that in normal galaxies.

5. CONCLUSION

We develop a steady-state model for the secondary electrons and try to estimate the synchrotron radiation of the secondary electrons for the radio emission of the ULIGs. Comparing with the observations of a sample of the ULIGs, our calculation shows that there are two types of ULIGs according to the derived magnetic field. We show that the synchrotron radiation of the secondary electrons is significant for the radio emission of some ULIGs.

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