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Gravitationally Lensed Galaxy Number Counts in the Infrared I: Concept

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Abstract: Gravitational lensing effect on infrared number counts is a useful tool for the study of galaxy evolution at high redshift. In contrast to the case of optical number counts, far infrared number counts are enhanced by the existence of gravitational lens. We introduce the concept of the magnification bias and then formulate the gravitationally lensed number count of infrared galaxies. Then we show the possibility of utilizing the lensed number counts of the infrared galaxies as a tool for the study of galaxy evolution.

1. INTRODUCTION

Gravitationally lensed number count of galaxies is a unique probe of the deep Universe for many reasons. First of all, the physics is well-established, i.e. general relativity, and thus has a fundamental clarity. We next note that the lensing is basically a magnification phenomenon, therefore it works as a huge natural telescope. For complete understanding of gravitational lens, see Schneider, Ehlers, & Falco (1992). A comprehensive review is also given by Narayan & Bartelmann (1999).

Until recently, the lensed number count has been studied mainly at optical wavelengths, in relation to both cosmology and galaxy evolution (e.g. Broadhurst et al. 1995). Now we know that far-infrared (FIR) wavelengths are of crucial importance for the study of galaxy evolution. At present, it is generally recognized that FIR wavebands are not well suitable for the investigation of ultra high-z objects ($z > 2-3$), because the peak of the blackbody emission goes away toward sub-mm by redshift. Thus the effect of the ultra high-z galaxy evolution is less prominent at far-infrared wavelengths compared with the longer wavelengths, if unlensed. However, the gravitational lensing effect on the infrared galaxy number counts counteracts this drawback. If the slope of the number count, $\mathrm{d}\log N/\mathrm{d}\log S > -1$, the galaxy count is suppressed by lensing (so called depletion). This is the case of optical galaxy number count. In contrast, if $\mathrm{d}\log N/\mathrm{d}\log S < -1$, the galaxy count is enhanced by lensing, and this is the

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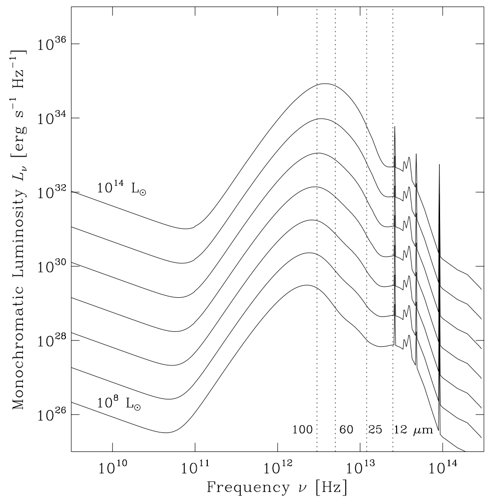

Fig. 1: Assumed galaxy spectral energy distribution in the near infrared to radio wavelengths. Vertical dotted lines represent the wavelengths of *IRAS* four bandpasses.

case of the infrared number count. Recently ISO observations of the lensed galaxy counts have been reported (e.g. Altieri et al. 1999).

Therefore the gravitationally lensed number count will be an interesting subject for next generation FIR space missions such as HII/L2 (SPICA), Japanese 3.5-m infrared space telescope project (Nakagawa et al. 1998), due to its high angular resolution. In this paper we show the basic formulation of the gravitationally lensed galaxy number counts in the FIR wavelengths. Concrete examples of the lensed number count estimation by galaxy clusters are extensively discussed in Yonehara et al. (2000).

2. GALAXY NUMBER COUNT MODEL

The galaxy number count model is represented by galaxy SEDs, LF, cosmology, and galaxy evolution. We review the framework of the number count model in this section. For details of the model, see Takeuchi et al. (2001).

2.1 Spectral Energy Distribution

The infrared – radio galaxy SED is modeled by the superposition of the following components. For the infrared – sub-mm component, we consider PAH (polycyclic aromatic hydrocarbon), graphite and silicate dust spectra (Dwek et al. 1997). In the case of the radio-quiet sources, emission at millimeter wavelength regime is dominated by synchrotron radiation explained by supernova remnants (Condon 1992).

By considering the above, we construct the infrared model SEDs based on the *IRAS* color–luminosity relation (Smith et al. 1987; Soifer & Neugebauer 1991). Smith et al. (1987) and Soifer & Neugebauer (1991) found that the *IRAS* FIR colors and FIR luminosity are tightly correlated. The relation reported by Soifer & Neugebauer (1991) is slightly nonlinear, but also a monotonic function of L_{60}. We interpreted this relation to the dust temperature $T_{\rm dust}$–

L_{60} relation and calculated the modified blackbody continuum with corresponding $T_{\rm dust}$. We adopted the dust emissivity $\varepsilon_\nu \propto \nu^\gamma$ with $\gamma = 1.5$.

We, then, utilized the data provided by Soifer & Neugebauer (1991) and derived the approximately linear relation between *IRAS* flux densities, S_{60} and S_{25}. We thus added the mid-infrared spectra proposed by Dwek et al. (1997) to the FIR component so that the superposed spectra reproduce the correlation reported by Smith et al. (1987), such that $\log S_{25}/S_{60} \simeq -0.9$. The unidentified infrared bands (UIBs), which we assumed to be produced by PAHs, are also an important component of the IR SEDs of galaxies. We set the continuum-to-band intensity ratio as reported by Dwek et al. (1997). Detailed properties of PAHs are taken from Allamandola et al. (1989); e.g. we set the PAH features at 3.3 μm, 6.2 μm, 7.7 μm with a broader component at $5.5 - 9.5$ μm, and 11.3 μm.

The remarkably tight and ubiquitous correlation is well-known between the FIR continuum flux and radio continuum flux. For the longer wavelength regime, power-law continuum produced by synchrotron radiation ($\propto \nu^{-\alpha}$) dominates the observed emission. We set $\alpha = 0.7$ according to Condon (1992), and added the FIR composite spectra. Here we have the final SED we use in our number count and CIRB models (see Figure 1).

2.2 Local Luminosity Function and Evolutionary Effect

We adopted the 60-μm LF based on the *IRAS* by Soifer et al. (1987) as the local IR LF of galaxies:

$$\log \phi_0(L_{60}\ [L_\odot]) = \begin{cases} 4.87 - 0.73 \log L_{60}\ [L_\odot] & \text{for } 10^8 < L_{60} < 10^{9.927}; \\ 18.5 - 2.1 \log L_{60}\ [L_\odot] & \text{for } 10^{9.927} < L_{60} < 10^{13}; \\ \text{no galaxies} & \text{otherwise,} \end{cases} \tag{1}$$

where ϕ_0 is the number density of galaxies in a unit of Mpc^{-3}dex^{-1}. We show the LF in the upper panel of Figure 2. We applied the double power-law form for the local LF. We assumed pure luminosity evolution in this study. In this case 60-μm luminosity of a certain galaxy at redshift z is described as

$$L_{60}(z) = L_{60}(0) f(z)\ , \tag{2}$$

We also assumed that the luminosity evolution is 'universal', i.e. independent of galaxy luminosity. This is depicted in the lower-left panel of Figure 2.

2.3 Formulation of the Galaxy Number Count

Using the above formulae, we calculate the flux–number ($\log N - \log S$) relation, or so-called galaxy number count. We assume that galaxies are regarded as point sources (i.e. the cosmological dimming of surface brightness is not taken into account). Then the relation between observed flux $S(\nu)$ and emitted monochromatic luminosity $L(\nu_{\rm em}) = L((1+z)\nu)$ is given by

$$S(\nu) = \frac{(1+z) L\left((1+z)\nu\right)}{4\pi d_{\rm L}^2}\ , \tag{3}$$

where $d_{\rm L}$ is luminosity distance. When we fix a certain $S(\nu)$, we obtain $L((1+z)\nu)$ by using equation (3). Then the corresponding $L_{60}(S(\nu),\ z)$ at the redshift z is uniquely determined.

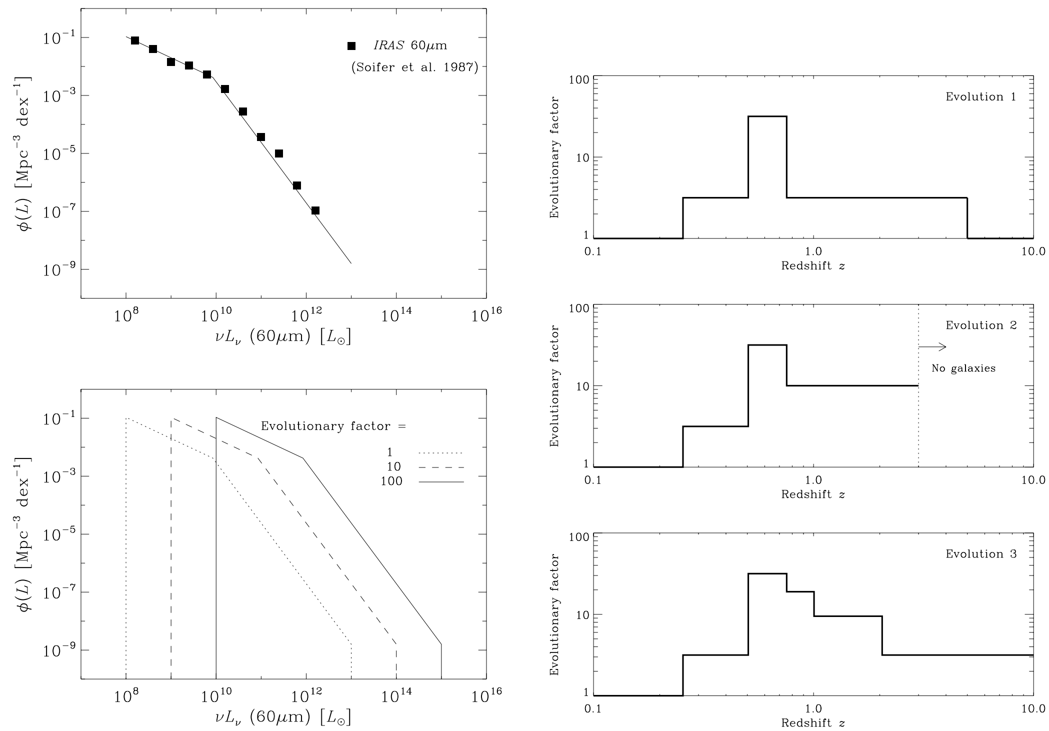

Fig. 2: Upper left panel: the applied 60-μm luminosity function (LF) in this paper. This LF is derived by Soifer, Houck, & Neugebauer (1987). Lower left panel: schematic representation of its evolution as a function of redshift. Right panel: the three evolutionary factors we used in this study.

We define $N(> S(\nu))$ as the number of galaxies with a detected flux density larger than $S(\nu)$ in a unit of solid angle [sr^{-1}], formulated as

$$N(> S(\nu)) = \int_0^{z_{\max}} \mathrm{d}z \frac{\mathrm{d}^2 V}{\mathrm{d}z\, \mathrm{d}\Omega} \int_{L_{60}(S(\nu),z)}^{\infty} \phi(z,\, L'_{60})\, \mathrm{d}L'_{60}\ , \tag{4}$$

where $\mathrm{d}^2V/\mathrm{d}z\mathrm{d}\Omega$ is the comoving volume element per sr and $z_{\max}$ is the maximum redshift we consider in this study.

We then formulate the number count with evolution. If pure luminosity evolution takes place, by using equation (2), the evolution of the luminosity function with redshift is expressed as

$$\phi(z, L_{60})\, \mathrm{d}L_{60} = \phi_0\left(\frac{L_{60}}{f(z)}\right)\ \mathrm{d}\left(\frac{L_{60}}{f(z)}\right) \tag{5}$$

where $\phi_0(L_{60})$ is the IR LF in the local Universe. The expected number count is expressed as

$$\begin{aligned} N(> S(\nu)) &= \int_0^{z_{\max}} \mathrm{d}z \frac{\mathrm{d}^2 V}{\mathrm{d}z\, \mathrm{d}\Omega} \int_{L_{60}(S(\nu),z)}^{\infty} \phi_0\left(\frac{L_{60}{}'}{f(z)}\right)\ \mathrm{d}\left(\frac{L_{60}{}'}{f(z)}\right) \\ &= \int_0^{z_{\max}} \mathrm{d}z \frac{\mathrm{d}^2 V}{\mathrm{d}z\, \mathrm{d}\Omega} \int_{L_{60}(S(\nu),z)/f(z)}^{\infty} \phi_0(\tilde{L}'_{60})\ \mathrm{d}\tilde{L}'_{60} \end{aligned} \tag{6}$$

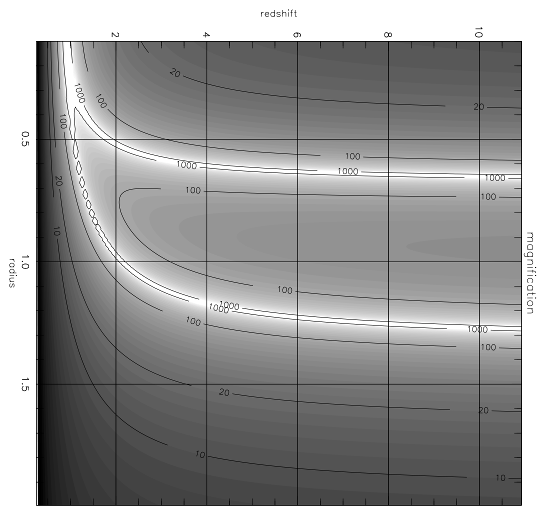

Fig. 3: Lens magnification factors as a function of angular position with respect to the lens and source redshift. The lens redshift is $z = 0.25$ in this figure.

where $\tilde{L}_{60} = L_{60}/f(z)$. In this study we used three representative evolutionary factors shown in the right panel of Figure 2.

3. THE EFFECT OF GRAVITATIONAL LENSING ON THE NUMBER COUNT

In this section, first we see the fundamental concepts of lensed number count, the so-called *magnification bias*. For this purpose, first we treat a quite simple case as follows.

Consider the case that the unlensed number count is expressed as a power law

$$\log N_0(> S) = \gamma \log S + C \ , \tag{7}$$

($\gamma < 0$ and $C = \text{const}$). If the lensing exists and the magnification factor is A at a certain position on the sky, the source is brightened as $\log S' = \log AS = \log S + \log A$. Then the number count becomes

$$\begin{aligned} \log N_1(> S) &= \gamma(\log S - \log A) + C \\ &= \log N_0(> S) - \gamma \log A \ . \end{aligned} \tag{8}$$

Thus we have

$$N_1(> S) = N_0(> S)\, 10^{-\gamma \log A} = N_0(> S)\, A^{-\gamma} \ . \tag{9}$$

In addition, we should consider the second effect, magnification of the sky area, which decreases the surface density of galaxies as

$$N_2(> S) = N_0(> S)\, A^{-1} \ . \tag{10}$$

Considering these effects together, we have

$$N_{\rm lens}(> S) = N_0(> S)\, A^{-(\gamma+1)} \ . \tag{11}$$

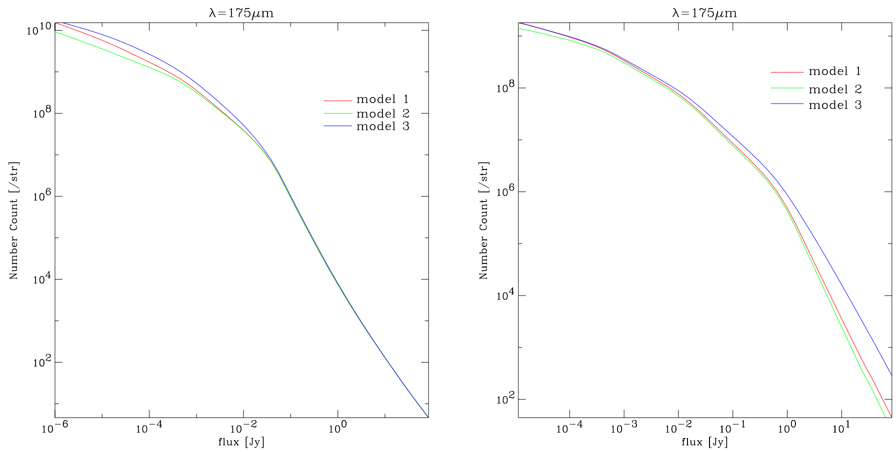

Fig. 4: The gravitational lensing effect on a galaxy number count at 175 μm. Left panel: the unlensed number counts produced from evolution models 1, 2, and 3. Right panel: the gravitationally lensed number counts from the same models as unlensed counts.

This phenomenon is called the magnification bias. Equation (11) shows that the count is unchanged by lensing, in the case that the number-count slope $\gamma = -1$. Therefore, as we mentioned in Section 1, if the slope is steeper than $\gamma < -1$, the lensing works as an enhancement of the number count. Recent observations show that the FIR galaxy number count has a very steep slope of $\gamma \lesssim -2.5$, so the lensing makes the detection of the FIR sources more effective.

Next we consider a more realistic case. Magnification A is a function of the position on the sky, $\boldsymbol{\theta}$. More importantly, A strongly depends on the redshifts of source and lens. We treat the gravitational lensing by clusters of galaxies as discussed in Yonehara et al. (2000). Since the unlensed number count is expressed as

$$N_0(>S) = \int_0^\infty \mathrm{d}z \frac{\mathrm{d}^2 V}{\mathrm{d}z \mathrm{d}\Omega} \int_{L_{60}(S,z)}^\infty \phi(L', z)\, \mathrm{d}L' \,, \tag{12}$$

the lensed number count is

$$N_{\mathrm{lens}}(>S) = \frac{\displaystyle\int_0^\infty \mathrm{d}z \int_\Omega \mathrm{d}^2\boldsymbol{\theta} \frac{\mathrm{d}^2 V}{\mathrm{d}z \mathrm{d}\Omega} \int_{L_{60}(S/A,z)}^\infty \phi(L', z) A(z, \boldsymbol{\theta})^{-1}\, \mathrm{d}L'}{\displaystyle\int_\Omega \mathrm{d}^2\boldsymbol{\theta}} \,. \tag{13}$$

The magnification $A(z, \boldsymbol{\theta})$ generally has two poles at a certain z, and is very large around the poles. We show the lens magnification factors as a function of angular position with respect to the lens and source redshift in Fig. 3, where the lens redshift is assumed to be $z = 0.25$. Thus, if the lens model is well established, we will obtain the information of the luminosity distribution (i.e. LF) of the infrared galaxies at the redshift of our interest. In Fig. 4, the difference of the unlensed number counts in the faintest regime is reflected in the brightest regime of the lensed number counts.

4. SUMMARY

Gravitational lensing is regarded as a huge natural telescope and provides a unique probe of distant galaxies. In contrast to the case of optical number count, far infrared number count is enhanced by the existence of gravitational lens. We introduced the concept of the magnification bias and then formulated the gravitationally lensed number count of infrared galaxies. We showed the possibility of utilizing the lensed number count of the infrared galaxies as a tool for the study of galaxy evolution. Concrete examples are shown in Yonehara et al. (2000).

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