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Far-Infrared Emission of Intracluster Dust (ICD)

By

Nobuo ARIMOTO*, Toshinobu TAKAGI†, and Hitoshi HANAMI‡

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Abstract: In the young universe, clusters of galaxies could be bright FIR-Submm sources due to the dust emissions from young ellipticals. The intracluster dust (ICD) could also contribute to the FIR-Submm emissions considerably, but the ICD is fragile in the ambient hot ICM. Therefore, a chance to detect the ICD emission would be much smaller than the dust emissions from galaxies. Dust emissions from elliptical galaxies (EROs) in the young Coma cluster at a distance of $z = 2 - 3$ would be easily detected by a future mission of H2L2 satellite, thus the FIR-Submm survey would become a powerful tool for searching high-z clusters.

1. INTRODUCTION

Clusters of galaxies could be significant FIR-Submm sources in the young universe. Clusters at high redshifts are difficult to find, and only a few clusters beyond $z = 1$ are known. Most of them are discovered by looking for a clustering of red objects around quasars or radio galaxies. Well defined colour-magnitude (CM) relations in the form of red sequences or red fingers are identified in all of these clusters, which clearly indicates that bright cluster members are all passively evolving elliptical galaxies. These high-z clusters are likely to be progenitors of rich clusters of galaxies, like the Coma in the local universe. Without a single exception, the CM relations of ellipticals in clusters are found to be universal. They are the sequences of ellipticals with increasing stellar metallicity towards the brighter end, evolving passively after an early epoch of intensive star formation. Indeed, it is suggested that the major epoch of star formation, or in other words, the epoch of galaxy formation could be derived from evolutionary behaviors of the CM relations of ellipticals in clusters at $z > 1.3$ (Kodama et al. 1998). However, a search for high-z clusters turns out to be extremely difficult. X-ray ICM search and IR imaging of clustering red galaxies were attempted, but no clusters have yet been discovered beyond $z > 1.3$. In the early universe, 1) clusters might not have acquired the ICM yet to give rose to X-ray emission, 2) the spectral energy distributions (SEDs) of ellipticals could be quite different from

* Institute of Astronomy, University of Tokyo, 2-21-1 Osawa, Mitaka, Tokyo 181-0015, JAPAN; arimoto@mtk.ioa.s.u-tokyo.ac.jp
† Department of Physics, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima-ku, Tokyo 171-8501, JAPAN
‡ Faculty of Human Science, Iwate University, 3-18-8 Ueda, Morioka, Iwate 020-8550, JAPAN

those predicted by a model of passively evolving galaxies, or 3) assembles of galaxies were so weak as to be identified as clusters. However, clusters of galaxies should be strong FIR-Submm sources and a search for clusters by using FIR-Submm detectors would be an efficient approach to look for high-z clusters. Young star forming ellipticals should be dust-rich, thus clusters should appear as clusterings of extremely red objects (EROs). Dust could be outflowing from young ellipticals *via* galactic winds and/or ram pressure stripping and would form intracluster dust (ICD). The ICD would then be heated by the radiation field of young ellipticals first and later heated further by an accreting hot X-ray gas which eventually destroys the ICD by sputtering. The ICD FIR emission is indeed suggested by a recent ISO observation of the Coma cluster (Stickel et al. (1988)). In this article, we show that FIR-Submm emissions of clusters of galaxies at high redshifts are well within the reach of next generation FIR satellites such as HII/L2 mission planned in Japan.

2. MODEL

We have developed a model for spectral evolution of galaxies from UV to Submm wavelengths which solves the equation of radiative transfer by assuming spherical symmetry for arbitrary radial distributions of stars and dust in a galaxy. Isotropic multiple scattering is assumed and self-absorption of re-emission from the dust grains is fully taken into account. Following a prescription given by Draine & Lee (1984), we adopt a dust model consisting of graphite and silicate grains (75% in mass), very small graphite grains (VSGs, 10%), and polycyclic aromatic hydrocarbons (PAHs, 15%). Large grains have a size distribution given by $g(a) \propto a^{-3.5}$ for $a > 100$Å, while VSGs have $g(a) \propto a^{-4.2}$ for $10\text{Å} \leq a \leq 100$Å. Temperature fluctuation of VSGs and PAHs are explicitly calculated. Our model reproduces the extinction curve and the spectrum of cirrus emission in the Milky Way. Intrinsic SEDs of galaxies (i.e., without the effects of dust) are taken from Kodama & Arimoto (1997), in which the SEDs are calculated consistently with chemical evolution. We assume that the SED of a galaxy is dominated by diffusely distributed stars and dust whose distributions are both given by King's law:

$$\rho(r) = \frac{\rho_0}{(1+(r/r_c)^2)^{3/2}},$$

where ρ_0 is the density at the centre of galaxy and r_c is a core radius. We fix the geometry of stars and change the dust distribution by choosing a value of parameter $\eta = r_{c,D}/r_{c,S}$, where $r_{c,D}$ and $r_{c,S}$ are the core radii of dust and stars, respectively. In the following sections, $\eta = 100$, 1000, and 1.6 are adopted for passively evolving ellipticals, star forming young ellipticals, and clusters of galaxies, respectively. A detailed description of our model is given in Takagi, Vansevičius, & Arimoto (1999).

3. ELLIPTICALS AND EXTREMELY RED OBJECTS

We have used a galactic wind model of Kodama & Arimoto (1997) that reproduces well the CM relation of E/S0 galaxies in Coma cluster. Figure 1 shows the rest-frame evolution of SEDs for giant elliptical galaxies in the Coma cluster ($M_V = -23$ mag at $t = 12$ Gyrs). No dust is considered. At 0.2 Gyr, well before the onset of supernovae-driven wind, ellipticals become most luminous and could be identified as young galaxies. Notable features of the SEDs of young galaxies are prominent fluxes at UV regions ($0.1 - 0.4$ μm) dominated by young massive stars. However, the SED evolution of young ellipticals shown in Figure 1 is wrong, because intense starburst should be followed by numerous supernovae explosions which eject the gas that contains considerable amount of heavy elements and dust. The dust would also be produced in circumstellar envelopes of evolving AGB stars and would eventually be spread out into the space *via* stellar winds. Thus, young ellipticals should certainly contain significant amount of the dust.

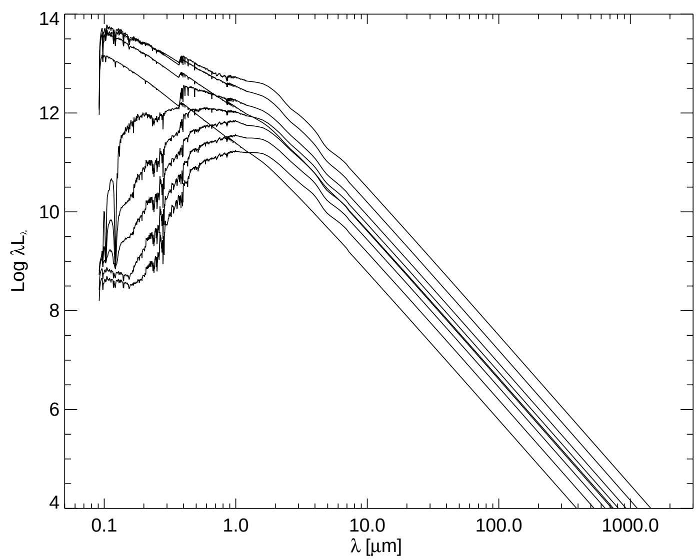

Fig. 1: SED evolution of a galactic wind model (Kodama & Arimoto (1997)); $t = 0.02$, 0.05, 0.10, 0.20, 0.50, 1.0, 2.0, 5.0, and 12.0 Gyrs The galactic wind occurs at $t = 0.36$ Gyrs. No dust extinction.

Figure 2 shows the evolution of SEDs for the same model as in Figure 1 but with dust extinction in UV-optical and re-emission in NIR-FIR-Submm wavelengths. The galactic wind occurs at $t = 0.36$ Gyrs in this model. Like starburst galaxies in the local universe, intense star formation is underway earlier than the wind in dust-rich young ellipticals, after which ellipticals evolve passively without any emissions from dust. Except for a very early stage ($t = 0.02$ Gyrs), during which ellipticals contain little dust due to inefficient chemical enrichment, young ellipticals before the onset of wind always show conspicuous thermal emissions from the dust at MIR-Submm wavelengths. Several emission lines from PAHs and continuous emission from thermalized grains at the submm range are prominent. On the contrary, the UV-optical parts of SEDs are heavily obscured by the dust, which naturally explains why all previous attempts failed in searching for young ellipticals in optical bands. Our simple model suggests that a cluster of young dust-rich ellipticals would be a strong FIR-Submm source in the high-z universe.

Extremely red objects (EROs) are by definition objects, presumably at high-z, that have considerably red colours ($R-K > 5$). Some of them could be nearby Galactic M-type stars, but most of them are galaxies at $z > 0.8 - 0.9$. EROs could be either passively evolving ellipticals or dust-rich starburst galaxies at high redshifts. Figure 3 shows the $R-K$ evolution of cluster ellipticals in the observer's frame. Galaxies are assumed to form at $z_f = 5$ and cosmological parameters assumed are $H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0.5$ and $\Lambda = 0$. Vertical solid and dashed lines indicate the evolution of CM relation of Coma ellipticals with and without dust effects, respectively. Solid, dotted, and dash-dotted curves show redshifted colours of three starburst

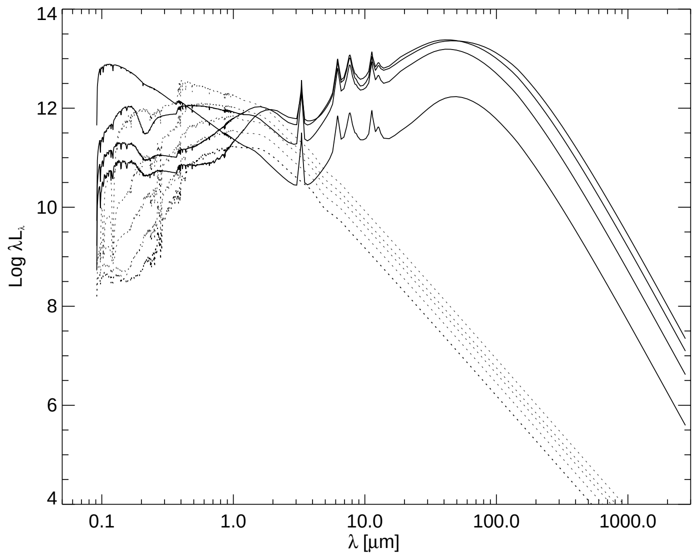

Fig. 2: The same as Figure 1, but a model takes into account dust extinction and emission explicitly for stages before the wind ($t = 0.02$, 0.05, 0.10, 0.20 Gyrs). The optical depth assumed is $\tau_V = 12$.

galaxies M82, Arp220, and HR10, respectively. Filled triangles and open circles are observed EROs. True, it is rather difficult to say if EROs are passively evolving ellipticals or if they are star forming dust-rich galaxies, but the locations of EROs shown in Figure 3 are all consistent with the evolutionary behavior of passively evolving ellipticals. In particular, a clustering of EROs at $z \simeq 1.2 - 1.3$ is very likely to be a cluster of dust-rich ellipticals. If so, it could be the cluster at the highest redshift ever known. Dust-rich ellipticals are systematically redder than dustless ones, but the dust effect becomes apparent only at the redshift beyond $z \simeq 1.5$. The diagram provides a powerful tool to identify clusters of galaxies at $z > 2$. Kodama et al. (1998) derived an epoch of galaxy formation, $z_f > 2.5 - 4.5$, by following the evolution of CM relation of cluster ellipticals. Clusters beyond $z > 2$ will give a definitive value of z_f, but it must be kept in mind that z_f should be estimated using models that take into account the dust, otherwise the resulting z_f would be erroneously large.

4. ICD EMISSION OF COMA CLUSTER

An ISO detection of the extended FIR emission from the Coma cluster of galaxies was reported by Stickel et al. (1988), who interpreted it as thermal emission from the intracluster dust (ICD) with a temperature slightly higher than the Galactic foreground cirrus. In a way similar to Dwek, Rephaeli, & Mather (1990), we have calculated the thermal emission from the ICD in Coma. Whatever its origin is, the dust in intracluster space would be heated by UV photons from cluster galaxies and also heated stochastically by the ambient hot gas and undergoes temperature fluctuations. We assume the King distributions for galaxies, the hot gas, and the dust; the latter two have identical distribution with $\eta = 1.6$ with respect to the galaxy distribution (Dwek, Rephaeli, & Mather 1990). A radial gradient of gas temperature is explicitly considered by adopting the observed one for the Coma cluster (Henriksen & Mushotzky 1986). For simplicity, we assume all cluster galaxies as ellipticals.

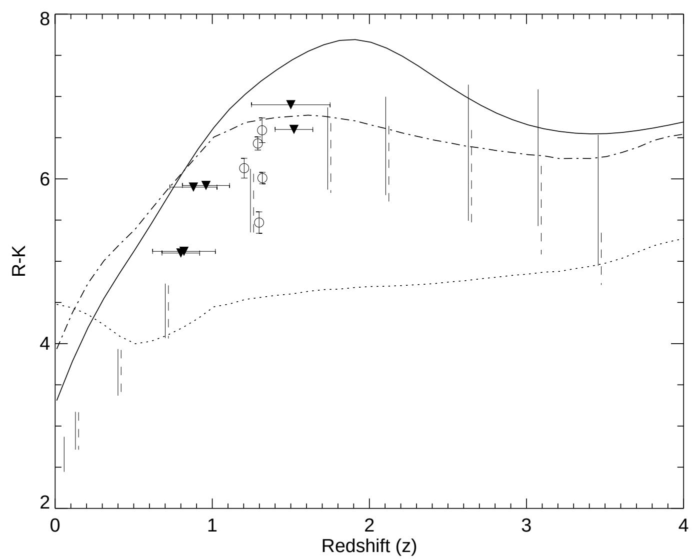

Fig. 3: R-K evolution of Coma ellipticals with dust (vertical solid line) and without dust (vertical dashed line).

Figure 4 shows the dust emission profile across the central region of the Coma cluster at 120 μm wavelength. The amount of dust is adjusted in such a way that the resulting $F_{120\ \mu m}$ at the cluster center agrees with the observed flux. The model profile reproduces the observed one fairly well, although the model gives slightly extended profile. Figure 5 shows the NIR-Submm SEDs of the Coma cluster. The SED of ICD heated by cluster ellipticals is given by a dashed line, while that of ICD heated by the hot ICM is given by a dot-dashed line. The total SED of ICD is shown by a solid line. For an illustrative purpose, the SED of a giant elliptical galaxy with dust is also presented. The thermal emission heated by the hot X-ray gas dominates the ICD emission, while the ICD heated by the galactic radiation field is almost negligible. Generally it is considered that the ICD is destroyed quickly due to sputtering by the hot gas. The ISO detection of 120 μm emission, thus, suggests 1) that the ICD was recently formed *via* galaxy merging and/or cluster merging, or 2) that Coma acquired the ICM very recently and there was not enough time to destroy the ICD, or 3) that ICD is localized in warm ICM whose temperature is not high enough to destroy the ICD, or 4) that the dust is continuously supplied from cluster galaxies either *via* winds or ram pressure stripping.

5. MIR-SUBMM SEDS of HIGH-Z CLUSTERS

In the young universe, galaxies assembled first, and then its clusters. It is not well understood whether the hot gas accreted after a cluster had formed or the gas had been associated with individual galaxies. Therefore, if galaxies had assembled first (stage 1), and if clusters formed later (stage 2), and if later the gas fell into the cluster potential (stage 3), dynamically young clusters of galaxies at high-z have a chance to be bright MIR-Submm sources. During the stage 1, young dust-rich ellipticals forming stars intensively should be luminous in the FIR and a clustering of these EROs can easily be identified in a FIR-Submm wide field survey. At the end of intensive star formation, the interstellar dust should be ejected into the intracluster

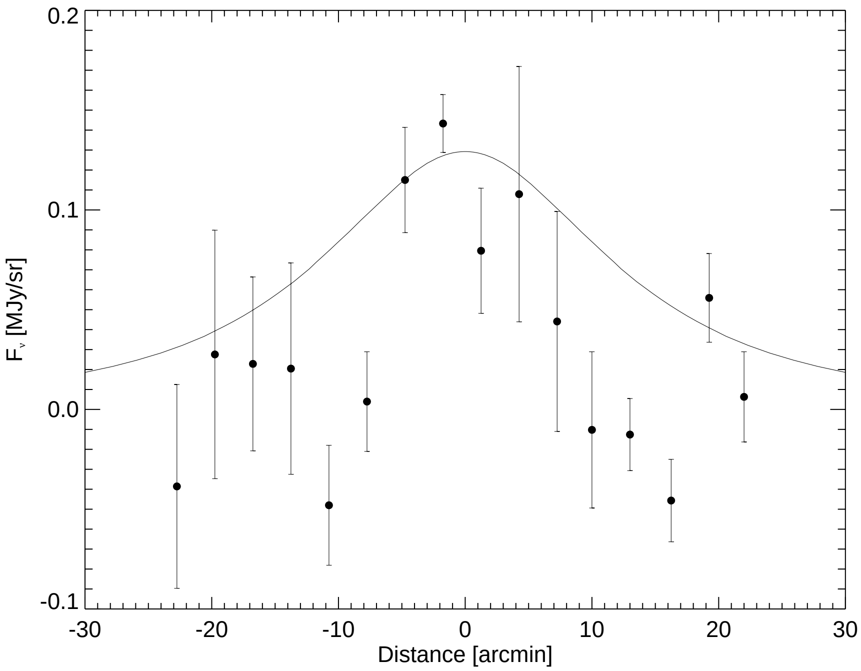

Fig. 4: A model profile of dust emission for the central part of Coma cluster. Flux is measured at $120\mu m$. Observational data of ISO are taken from Stickel et al. (1988).

space. Thus, during the stage 2, the ICD is most abundant and is heated effectively by young cluster ellipticals. If all heavy elements, now observed in the hot ICM, were frozen in the dust, the ICD heated by the galactic radiation field should provide strong MIR-Submm emission. It is the early phase of stage 3 when the ICD provides the most luminous FIR-Submm emission. During stage 3, the ICD would be heated by the accreting gas that quickly established the hot X-ray ICM. Before the dust is sputtered by the ICM, the ICD emits MIR-Submm radiation for a very short time interval. This phase could be called as a FIR flash of clusters. Once the hot X-ray ICM accumulates onto a cluster, the ICD evaporates and the FIR-Submm emissions decline quickly to the level of present day Coma.

Figure 6 shows the predicted SEDs of cluster galaxies and the ICD of Coma at an age of 1 Gyrs. With our cosmological parameters and a formation epoch $z_f = 5$ assumed, this age corresponds to $z = 2.63$. The dust in galaxies was much warmer than the ICD heated by the hot ICM, as a result of which young EROs (dotted line) dominated NIR-FIR emissions ($1\ \mu$m $\leq \lambda \leq 300\ \mu$m), while in the FIR-Submm wavelengths ($400\ \mu$m $\leq \lambda$) the emissions from the ICD (solid line) were prominent. Unfortunately, it would be rather difficult to detect these emissions by IRIS, but with the power and sensitivity H2L2 will certainly make it possible to detect the dust emission from young cluster ellipticals. If galaxies had already stopped star formation and yet the ICD was abundant enough to be heated by the ICM, the ICD emission could be detected at $10\ \mu$m $\leq \lambda \leq 50\ \mu$m and $\lambda \geq 300\ \mu$m. Thus, FIR-Submm searches for clusters of galaxies in the young universe beyond $z \sim 2$ are much more efficient than any other approaches such as a search for X-ray clusters and a survey of red galaxies surrounding quasars and/or radio galaxies.

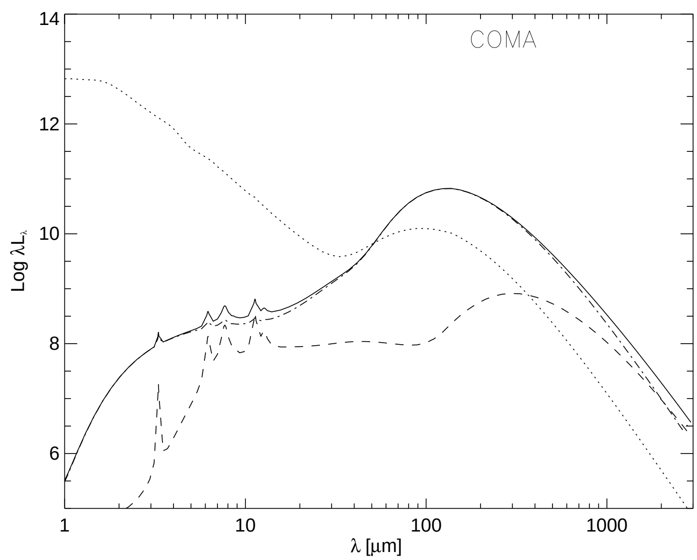

Fig. 5: ICD emissions in Coma cluster, heated by galaxies (dashed), the hot ICM (dot-dashed), and both (solid). Dotted line shows the total emission of cluster ellipticals.

6. SUMMARY

In the young universe, clusters of galaxies were bright FIR-Submm sources due to the dust emissions from young ellipticals. The ICD also contributed to the Submm emission considerably, but the ICD is fragile to sputtering by the hot ICM. Therefore, a chance to detect the ICD emission would be much less as compared to the detection of the dust emissions from galaxies. Dust emissions from elliptical galaxies (EROs) in the young Coma cluster at a distance of $z = 2.63$ would be easily detected in a future mission like HII/L2 satellite; thus the FIR-Submm survey would become a powerful tool for searching high-z clusters.

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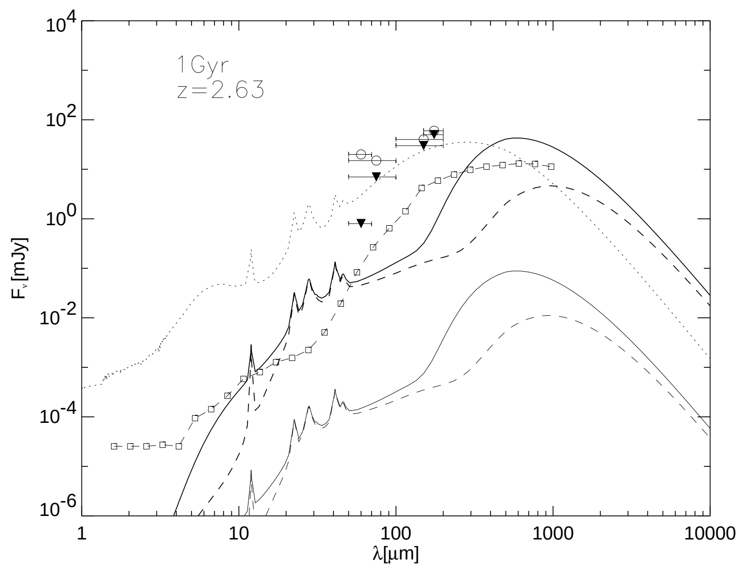

Fig. 6: Predicted SEDs for Coma cluster at $z = 2.63$. Solid lines show the total ICD emission dominated by emissions from dust heated by the hot ICM. Dashed lines give the ICD emission heated by young cluster galaxies. The upper lines indicate the SEDs with an assumption that all heavy elements observed today in the hot ICM were frozen in the ICD, while the lower ones assume the same amount of ICD detected by ISO in the present day Coma. Filled triangles and linked open squares indicate the detection limits of ASTRO-F and HII/L2, respectively.