論文の内容の要旨

論文題目：Molecular Gas in Late-stage Merging Galaxies
（衝突末期段階の銀河における分子ガスの観測的研究）

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We reveal the distribution and kinematics of molecular gas in colliding galaxy systems near the late-stage of their coalescence, called merger remnants (MRs). We statistically analyze their properties utilizing the largest-to-date survey of molecular gas. This is the first step in our series of studies which put emphasis on the cold molecular gas in MRs.

It has been long predicted from numerical simulations that a major merger of two disk galaxies results in a formation of the spheroid-dominated early-type galaxy (ETG). Contrary to this classical scenario of galaxy merger evolution, recent simulations with more realistic gas physics have shown that not all of the major mergers will become an ETG, but some will re-emerge as a disk-dominated late-type galaxy (LTG). However there has been no observational confirmation of this theoretical prediction. In order to verify this scenario and to investigate the evolution of galaxies after a merging event, we have conducted a carbon monoxide imaging survey of MRs in the local Universe using millimeter/submillimeter interferometers including ALMA, SMA, and CARMA, and the NRO 45 m single-dish telescope. Carbon monoxide (CO) is routinely used as a proxy of molecular hydrogen (H_2) in the Universe, as they are the second most abundant molecule after H_2 which is not easily observed due to their lack of dipole moments.

We investigate interferometric CO maps of 37 optically-selected MRs, including seven galaxies which were undetected in the CO line. Twenty seven of these galaxies were newly obtained, and 10 are archival data. By modeling the CO velocity distribution with circular motion, we find that 65 % (24/37) of the sample show kinematical signatures of a rotating molecular gas disk. The sizes of these disks vary significantly from 1.1 kpc to 9.3 kpc. We also find that the emission peaks are clearly shifted from the galactic centers in 75 % (18/24) sources with molecular gas disks, suggesting the presence of a ring and/or a bar. We were unable to model the remaining six sources using circular rotation. These galaxies show clumpy distribution and complex velocity fields, indicating that the molecular gas is still strongly disturbed and has not settled in the galactic plane.

We estimate the size ratio ($R_{\rm ratio}$) of the gas disk to the stellar spheroidal component for 24 MRs in order to investigate whether cold molecular gas disks are in extended form, as predicted from recent numerical simulations. The size ratios $R_{\rm ratio}$ for 54 % (13/24) of the MRs are less than unity. Six MRs which are bright at infrared wavelengths have compact molecular gas disks, which may have formed by past gas inflow that was triggered by dynamical instability following the merging. On the other hand, **46 % (11/24) of the MRs have gas disks which are extended relative to the stellar component**. We also discover a possible positive correlation between $R_{\rm ratio}$ and the total far-infrared luminosity. The molecular gas disks in the MRs show various properties, and we conclude that our sample includes MRs at different stages of their evolution, progenitors of galaxies with different characteristics, or different initial conditions.

The main motivation of this study is to investigate whether galaxy merging events can produce disk-dominated LTGs or they all result in spheroid-dominated ETGs. We expect MRs to show properties similar to ETG/LTGs, depending on which galaxy type they evolve into. We thus investigate whether molecular gas and stellar components in MRs share global properties with ETGs or LTGs, using a control sample. We use published data of ETGs from the $\rm ATLAS^{3D}$ project and LTGs from the BIMA-SONG project. The size of the molecular gas disks in MRs is similar to those in the ETGs rather than LTGs. The ratio of molecular gas mass to stellar mass, the gas mass fraction, is found to be in the range 1 – 10 % for MRs. The gas mass fractions of the LTGs are distributed around 10 %, whereas the gas mass fractions of the ETGs are distributed over a wide range between 0.1 % and 10 %. A Kolmogorov-Smirnov test suggests that the distribution of the gas mass fractions are different among the three samples. When the gas mass fractions of ETG/LTGs are combined, however, the MRs are not significantly different. These statistics are not inconsistent with the possibility that the MRs include progenitors of both ETGs and LTGs. In a diagram plotting $R_{\rm ratio}$ versus the gas mass fraction (Figure 1), the distribution of MRs does not overlap with either the ETG or the LTG population. In short, the molecular gas in MRs is on average similar to ETGs in terms of its disk size, but the MRs are in fact a distinct population with respect to their relation between size and mass relative to the stellar component.

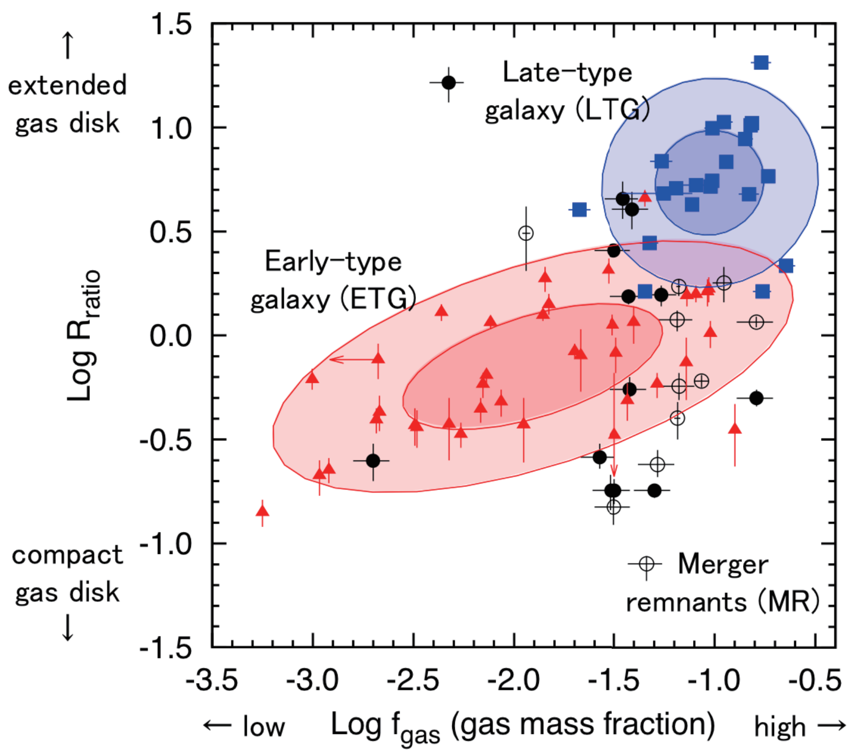

Figure 1: Relation between the gas mass fraction and relative size of the molecular gas disk to the stellar spheroidal component ($R_{\rm ratio}$). Black filled/open circles show the MRs whose molecular gas mass are estimated using interferometric/single-dish data, respectively. Red triangles and blue squares show ETGs and LTGs, respectively. The dark-red and light-red elliptical regions express the contour levels inside which the ETGs samples are included to within the 1 σ and 2 σ level, respectively. The blue elliptical regions are similar to the red ones, but for LTGs.

Overall, our conclusion is that 65 % of the MRs evolve into ETGs, 5 % into LTGs, 14 % into either ETG/LTGs, and 16 % into galaxies which cannot be classified into ETG/LTGs. Among the sources with observational signatures of molecular gas disks, we conclude that sources with a compact molecular gas disk will become ETGs regardless of the gas mass fraction, mainly because of the short depletion time of the molecular gas ($\sim 10^8$ yr), and high gas concentration in the nuclear region. On the other hand, we find that sources with an extended molecular gas disk and a large gas mass fraction are likely to result in LTGs, unless there are further mechanisms which transport the molecular gas toward the central region (e.g., nuclear bar) thereby decreasing the disk size. Confirming the evolution path of the sources with an extended molecular gas disk and a low gas mass fraction requires further studies to investigate whether a large amount of cold gas will settle on the extended gas disks by the returning of the ejected cold gas via tidal tails and cold gas accretion. For six MRs whose velocity fields cannot be modeled with circular rotation, their clumpy morphology and complex gas structure are not seen in either ETGs or LTGs. The seven MRs which were not detected in CO will evolve into ETGs earlier than the MRs with the molecular gas disks.

This study confirms, observationally, a new scenario that merging events are the crossroads of galaxy evolution, reprocessing them into a mixture of types including ETGs and LTGs.