論文の内容の要旨

Anomaly of Hydrogen Recombination Line Ratio in Ultraluminous Infrared Galaxies

（超高光度赤外線銀河における水素再結合輝線強度比異常）

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1. Introduction

Ultraluminous infrared galaxies (ULIRGs) radiate most ($\geq$ 90%) of their extremely large luminosities ($> 10^{12} L_{\odot}$) as infrared dust emission. Since their discovery in 1980's, it has been long debated which is the dominant energy source in ULIRGs: starburst activities and/or active galactic nuclei (AGNs). ULIRGs are thought to be dust-enshrouded quasars formed through the merger processes, eventually shedding their dust to evolve into quasars or massive ellipticals. Thus understanding the dust-obscured energy source of ULIRGs is important for investigating the merger-driven evolutionary scenario of galaxies. However, the large amount of dust in ULIRGs makes it difficult to investigate the energy sources observationally.

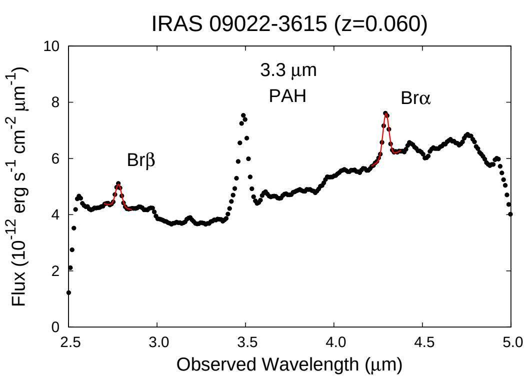

Figure 1 Example of the *AKARI* 2.5–5.0 μm spectra of ULIRGs. The best-fit Gaussian profiles for the Brα and Brβ lines are plotted with the red lines.

In order to avoid the effect of dust extinction, we focus on the near-infrared H I lines Brα (4.05 μm) and Brβ (2.63 μm) as a probe of starburst activities in ULIRGs. Since it is difficult to observe the lines

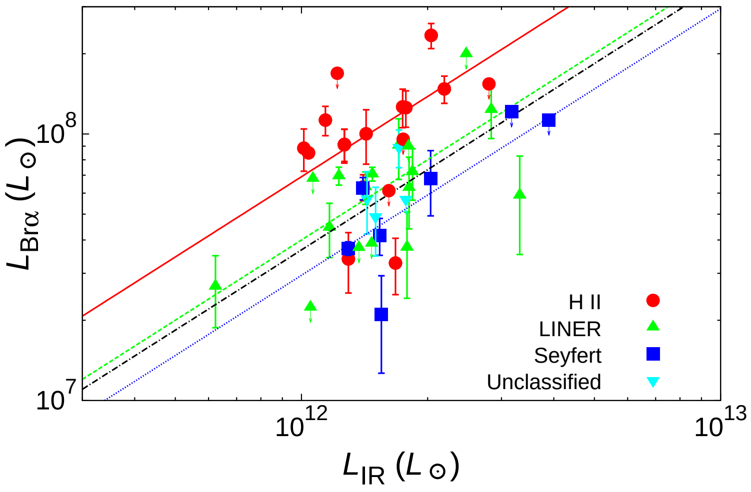

Figure 2 Comparison of the Brα line luminosity ($L_{Br\alpha}$) with the total infrared luminosity (L_{IR}). The symbols and colors represent the optical classifications of the galaxy. The red solid, green dashed, blue dotted, and black dashed–dotted lines indicate the mean $L_{Br\alpha}/L_{IR}$ ($L_{3.3}/L_{IR}$) ratio for H II galaxies, LINERs, Seyferts, and the combination of LINERs and Seyferts, respectively.

from the ground, we employ the 2.5–5.0 μm spectroscopic capability of the *AKARI* satellite. Figure 1 shows an example of the spectra, in which we can observe the Brα and Brβ lines at once. On the basis of the *AKARI* observations, we take two approaches to investigate the energy sources and the nature of starburst activities in ULIRGs in this thesis.

2. Starburst in ULIRGs

First, we focus on the Brα line and investigate the contribution of starburst activities as the energy source in ULIRGs quantitatively. The Brα line is predicted to be the brightest among the H I lines, which trace ionizing photons from OB stars and are used as an indicator of star formation, under heavy dust-extinction conditions ($A_V > 15$ mag). We conducted systematic observations of the Brα line in 50 nearby ($z < 0.3$) ULIRGs with *AKARI*. We detected the Brα line in 33 ULIRGs. The luminosity of the line ($L_{Br\alpha}$) correlates well with that of the 3.3 μm polycyclic aromatic hydrocarbon (PAH) emission ($L_{3.3}$). Thus we utilize $L_{3.3}$ also as an indicator of star formation in fainter objects where the Brα line is undetected. We compare $L_{Br\alpha}$ (or $L_{3.3}$) with the total infrared luminosity (L_{IR}) to investigate the contribution of starburst activities as the energy sources in ULIRGs. Figure 2 shows the comparison of $L_{Br\alpha}$ with L_{IR}. Among the 33 galaxies where the Brα line is detected, the mean $L_{Br\alpha}/L_{IR}$ ratio in LINERs/Seyferts is significantly lower than that in H II galaxies (the red line versus the green or blue line in Figure 2). This difference is reconfirmed with the $L_{3.3}/L_{IR}$ ratio in the larger sample (46 galaxies). Using the ratios, we estimate that the contribution of starburst in LINERs/Seyferts is (67 ± 9)%, and active galactic nuclei contribute to the remaining (33 ± 9)%. However, comparing the number of ionizing photons, $Q_{Br\alpha}$, derived from $L_{Br\alpha}$ with that, Q_{IR}, expected from star formation rate

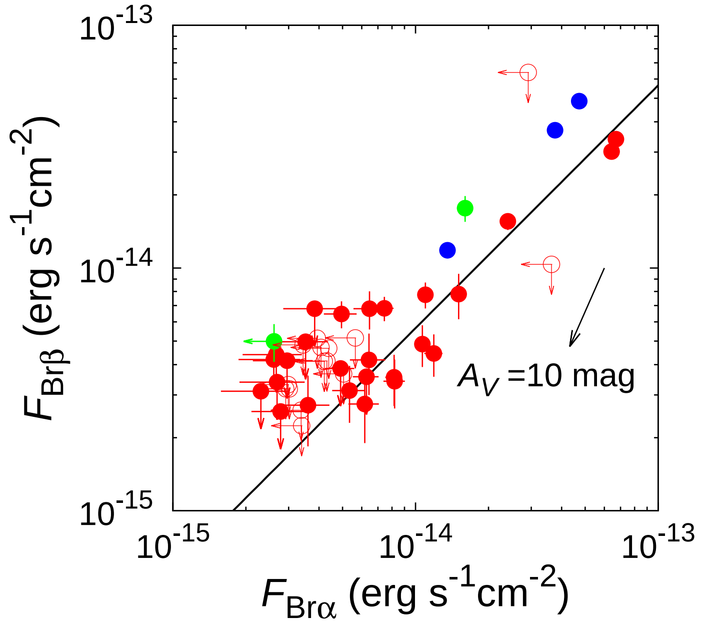

Figure 3 The Brα line flux ($F_{\mathrm{Br}\alpha}$) versus the Brβ line flux ($F_{\mathrm{Br}\beta}$). The solid line shows the theoretical line ratio in the case B condition: $F_{\mathrm{Br}\beta}/F_{\mathrm{Br}\alpha}$ = 0.565. The extinction vector in case of A_V = 10 mag is shown as the black arrow. The blue filled circles show galaxies with the high Brβ/Brα line ratio (higher than 0.565 with 3σ level) while red filled ones represent those with the normal ratio. The green filled circles show galaxies with the high Brβ/Brα line ratio, but are excluded from the discussion because of the large uncertainty in the determination of the underlying continuum of the lines. The red open circles represent galaxies where both the Brα and Brβ lines are not detected.

required to explain L_{IR}, we find that the mean $Q_{\mathrm{Br}\alpha}/Q_{\mathrm{IR}}$ ratio is only (55.5±7.5)% even in H II galaxies which are thought to be energized by pure starburst. We propose that dust within H II regions absorbs a significant fraction of ionizing photons.

3. Anomaly of H I Line Ratio

Next, in order to investigate the validity of the standard theory of H I line ratios, case B, in ULIRGs, we conducted systematic observations of the Brβ line in addition to the Brα line in 52 nearby ($z < 0.3$) ULIRGs with *AKARI*. We detected the Brα and Brβ lines in 31 ULIRGs. We show a comparison of the observed flux of the Brα line with that of the Brβ line in Figure 3. Among the 31 ULIRGs, three galaxies (shown as blue circles in Figure 3), IRAS 10494+4424, IRAS 10565+2448, and Mrk 273, show a Brβ/Brα line ratio (0.873 ± 0.074, 0.983 ± 0.053, and 1.029 ± 0.037, respectively) significantly higher than that of case B (0.565). The spectrum of Mrk 273 is shown in Figure 4 as an example. We cannot explain the high Brβ/Brα line ratio in the three galaxies with the combination of the case B theory and dust extinction since dust extinction could reduce but not increase the ratio. We explore possible causes of the high Brβ/Brα line ratio. If the Brackett lines are optically thin, we cannot explain the high Brβ/Brα line ratio with possible excitation mechanisms: recombination, collisional excitation, and resonant excitation. On the other hand, we show that the deviation of the Brβ/Brα line ratio from that of case B can be explained if the Brα line becomes optically thick while the Brβ line is still optically thin. We assume that the high Brβ/Brα line ratio is produced in an ensemble of H II regions with uniform density gas and each H II region is ionized by a single star. We simulate such H II regions with the Cloudy code and show that the high Brβ/Brα line ratio is explained when the column density of neutral hydrogen becomes large. Figure 5 shows the result of the Cloudy simulation. To achieve the column density large enough to make the Brα line optically thick within a single H II region, the gas density as high as $n \sim 10^8$ cm^{-3} is required. From this result, we propose an ensemble of H II regions, in each of which the Brα line is optically thick, can explain the high Brβ/Brα line ratio.

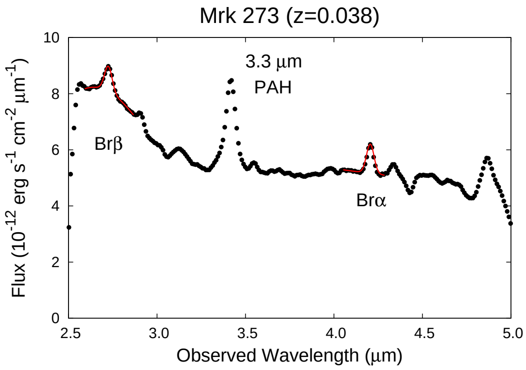

Figure 4 Example of Spectra of galaxies with high Brβ/Brα line ratio. The best-fit Gaussian profiles for the Brα and Brβ lines are plotted with the red lines.

It has been suggested that gas with a high temperature and a high density would yield a top-heavy initial mass function (IMF). If an extreme case of the top-heavy IMF is realized in the high-density starburst indicated by our model, the OB star population is much more enhanced than normal conditions. We propose this scenario as an explanation of the high efficiency of starburst in ULIRGs.

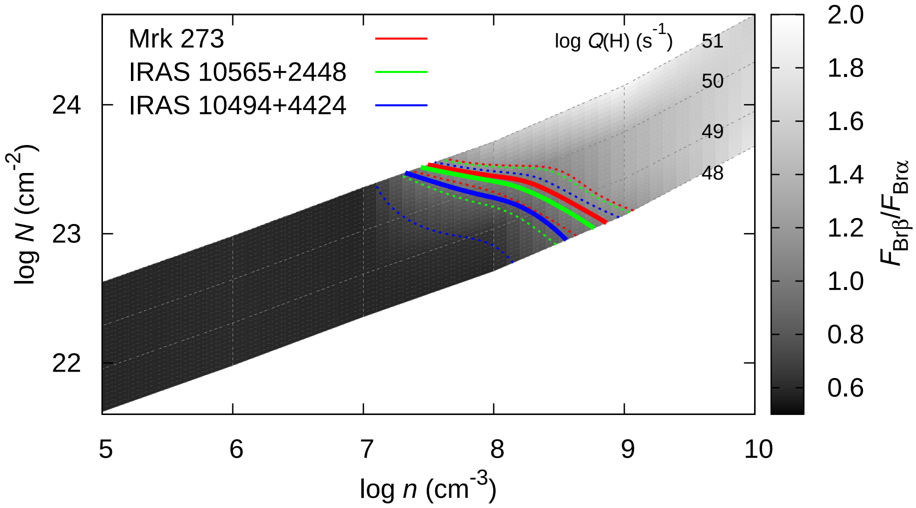

Figure 5 Cloudy result of the Brβ/Brα line ratio. The number of ionizing photons emitted by an ionizing source per unit time, Q(H), and n are varied within the ranges of 10^{48} s^{-1} $\leq Q$(H) $\leq$ 10^{51} s^{-1} and 10^5 cm^{-3} $\leq n \leq 10^{10}$ cm^{-3} with the intervals of a decade. The Brβ/Brα line ratio is shown as the gray scale. The observed Brβ/Brα line ratios of Mrk 273, IRAS 10565+2448, and IRAS 10494+4424 are presented as the red, green, and blue lines, respectively. The observed value is shown by the solid lines, and the range of the 3σ uncertainties are indicated by the dotted lines.