Anomaly of Hydrogen Recombination Line Ratio in Ultraluminous Infrared Galaxies

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ABSTRACT

We made systematic observations of the H I Brα (4.05 μm) and Brβ (2.63 μm) lines in 52 nearby ($z < 0.3$) ULIRGs with *AKARI*. Our observations show that ULIRGs have a tendency to indicate higher Brβ/Brα line ratios than those observed in Galactic H II regions, and three galaxies in the observed sample show the anomaly of the Brβ/Brα line ratios (~ 1.0), which are significantly higher than that of case B (0.565). The high Brβ/Brα line ratios cannot be explained by the combination of the dust extinction and the case B, since dust extinction reduces the ratio. We simulate H II regions in the ULIRGs with the Cloudy code, and show that the high Brβ/Brα line ratios can be explained with the combination of the optically thick Brα line and the optically thin Brβ line. To achieve the column density large enough to make the Brα line optically thick, the gas density is required as high as $n \sim 10^8$ cm^{-3}. Hence our results suggest that star-formation activity in ULIRGs occurs preferentially in high-density clouds.

Keywords: active galaxies, star formation, infrared galaxies, recombination lines

1. INTRODUCTION

Most of the large infrared luminosity in Ultraluminous infrared galaxies (ULIRGs) is thought to be produced by starburst activities (e.g., Veilleux et al. 2009). ULIRGs are estimated to have one of the highest star formation rate (SFR) of the order of $\sim 100\ M_{\odot}$ yr^{-1}, but the star-formation activity is heavily obscured by dust extinction. The large amount of dust harboured in ULIRGs makes it difficult to investigate the energy sources observationally, and thus it is important to estimate the amount of dust extinction in ULIRGs.

One of the most widely used indicators of dust extinction is the ratio of hydrogen recombination lines, especially the optical Hα and Hβ lines (e.g., Veilleux et al. 1995; Kim et al. 1998), The ratio of the H I line fluxes from photoionized gas can be numerically calculated with the assumption of the case B model (Osterbrock & Ferland 2006). However, in heavily dust-obscured objects such as ULIRGs, dust extinction is so high that the optical Balmer lines trace only the outer region of the object and could underestimate the extinction. To avoid this problem, we focus on the infrared H I lines Brα ($\mathcal{N} = 5 \to 4$, 4.051 μm) and Brβ ($\mathcal{N} = 6 \to 4$, 2.626 μm), which are less affected by dust extinction than optical ones.

The validity of the assumption of case B is, however, poorly investigated in H II regions in ULIRGs. We suppose that the large amount of gas in ULIRGs could make H I lines in addition to the Lyman series lines optically thick, and the case B assumption is not valid any more. This could make the line ratios significantly different from that of case B. We investigate this problem by systematically observing the Brα and Brβ lines in ULIRGs.

2. OBSERVATIONS

In order to investigate the Brα and Brβ lines systematically, we utilize the near-infrared spectroscopy of the *AKARI* infrared satellite (Murakami et al. 2007). The near-infrared spectroscopic observations were conducted with the InfraRed Camera (IRC) (Onaka et al. 2007) with the NG grism mode (Onaka et al. 2007) to obtain a 2.5–5.0 μm spectrum. The 1×1 arcmin^2 window is used to avoid source overlap. It has continuous 2.5–5.0 μm wavelength coverage, which is not achievable with ground-based telescopes due to Earth's atmosphere. With a single spectrum containing the both lines, we can estimate the Brβ/Brα line ratio reliably without observational bias such as the aperture difference.

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Among the pointed observations of *AKARI*, we focused on those conducted during the liquid-He cool holding period (Murakami et al. 2007, 2006 May 8 to 2007 August 26) to obtain high quality data. Among them, we further focused on the data taken with a mission program “Evolution of ultraluminous infrared galaxies and active galactic nuclei” (AGNUL; P.I. T. Nakagawa). We analyzed 52 spectroscopic data similar to those use by Yano et al. (2016). The data were processed using “IRC Spectroscopy Toolkit Version 20150331,” the standard IDL toolkit prepared for the reduction of *AKARI* IRC spectra (Ohyama et al. 2007).

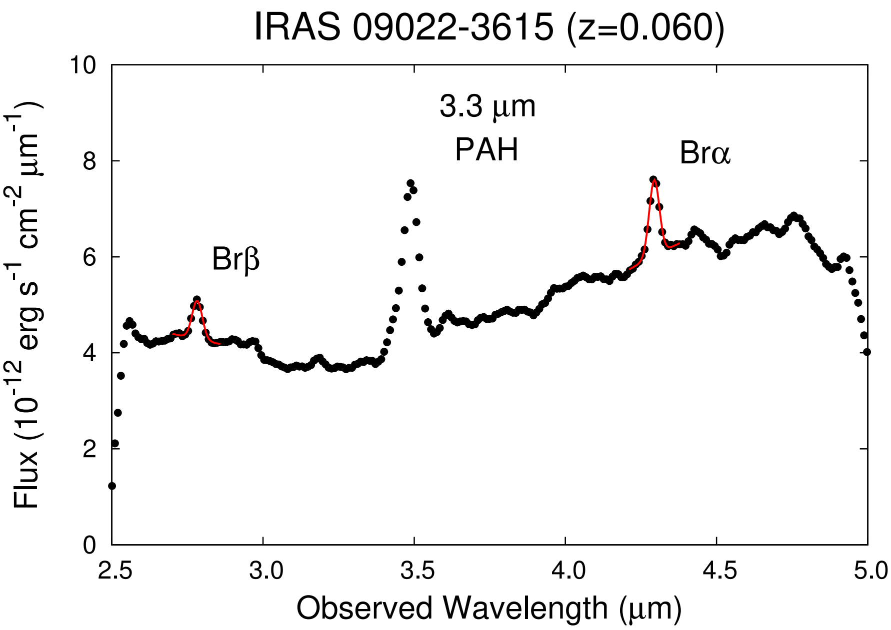

Figure 1. *AKARI* IRC 2.5–5.0 μm spectra of ULIRGs. The best-fit Gaussian profiles for the Brα and Brβ lines are plotted with the red lines.

In each spectrum, the Brα line at a rest-frame wavelength of $\lambda_{\rm rest}$ = 4.05 μm and the Brβ line at $\lambda_{\rm rest}$ = 2.63 μm are fitted separately with a linear continuum and a Gaussian profile. Figure 1 shows an example of the obtained spectrum. Both the Brα and Brβ lines can be seen clearly.

3. RESULTS

Figure 2 compares the observed the Brα line flux ($F_{\rm Br\alpha}$) with that of the Brβ line ($F_{\rm Br\beta}$) of our observed galaxies. The solid line shows the theoretical line ratio in the case B condition: $F_{\rm Br\beta}/F_{\rm Br\alpha}$ = 0.565. The extinction vector with A_V = 10 mag is shown as the black arrow. Galaxies located below the case B line in Figure 2 means that they have a Brβ/Brα line ratio lower than 0.565, which can be explained by the case B theory and dust extinction.

Figure 2 shows, however, shows that some galaxies are situated above the case B line. Especially, three galaxies IRAS 10494+4424, IRAS 10565+2448, and Mrk 273 have the Brβ/Brα line ratio (0.873 ± 0.074, 0.983 ± 0.053, and 1.029 ± 0.037, respectively) significantly (> 3σ) higher than that of case B (0.565). The line ratio above the case B line in Figure 2 means that the Brβ line is enhanced relative to the Brα line. This is opposite to the effect of dust extinction. Hence the line ratio of these galaxies cannot be explained by the combination of case B and dust extinction.

The three galaxies discussed above are relatively bright. In order to investigate whether the anomaly is found even in faint galaxies, we average the near-infrared spectra of 33 galaxies with $F_{\rm Br\alpha} < 10^{-14}$ erg s^{-1} cm^{-2}. Each spectrum is corrected for redshift and is averaged in rest wavelengths. We measure $F_{\rm Br\alpha}$ and $F_{\rm Br\beta}$ of the averaged spectrum with the Gaussian fitting and obtain $F_{\rm Br\alpha}$ = (2.58 ± 0.21) × 10^{-15} erg s^{-1} cm^{-2} and $F_{\rm Br\beta}$ = (2.05 ± 0.19) × 10^{-15} erg s^{-1} cm^{-2}. This yields the Brβ/Brα line ratio of 0.80 ± 0.10 (Figure 2), which is higher than the case B value of 0.565 with 2.3σ significance. Although the significance is not high enough (< 3σ), this is opposite to the expectation that ULIRGs show high dust extinction, i.e., the Brβ/Brα line ratio is lower than 0.565.

In summary, some of our observed ULIRGs show the Brβ/Brα line ratio significantly higher than the case B value and cannot not be explained by the effect of dust extinction. This suggests that the condition of H II regions in the ULIRGs with the anomaly high line ratio would be entirely different from that in the Galactic H II regions.

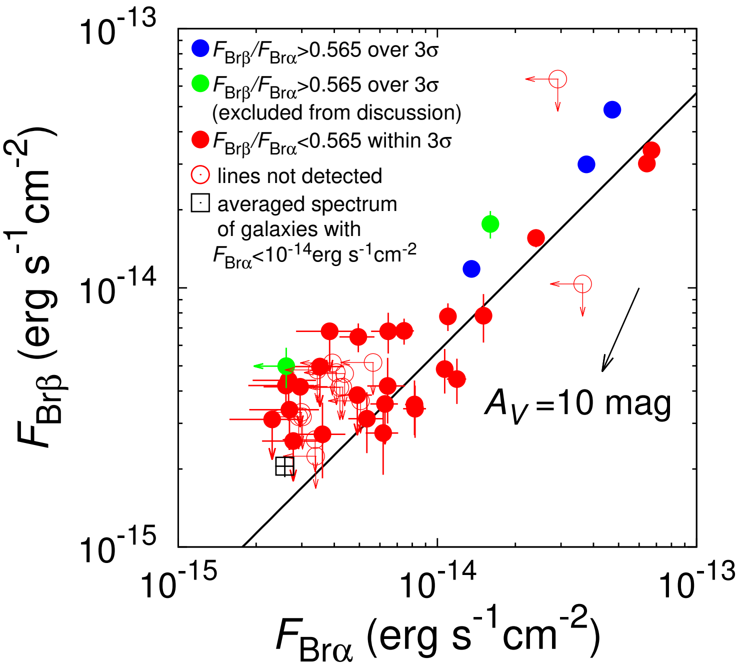

Figure 2. The Brα line flux ($F_{Br\alpha}$) versus the Brβ line flux ($F_{Br\beta}$). The solid line shows the theoretical line ratio in the case B condition: $F_{Br\beta}/F_{Br\alpha} = 0.565$. The extinction vector with $A_V = 10$ mag is shown as the black arrow. The blue filled circles show galaxies with the anomalous 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. The black open square shows the result of the averaged spectrum of 33 galaxies with $F_{Br\alpha} < 10^{-14}$ erg s^{-1} cm^{-2}.

4. DISCUSSIONS

4.1. Possibility of contamination

One possible cause of the line ratio anomaly is that the Brackett lines are contaminated by other features, but we cannot find any possible features which changes the Brackett line ratio significantly. We hence conclude that the anomalous Brβ/Brα ratio is intrinsic.

4.2. Optically thin cases

We firstly consider the case that the Brackett lines are optically thin. In this case, once the level population of neutral hydrogen is determined, the flux ratios of H I lines are fixed.

At low densities where the recombination process is dominant, the level population is represented by the case B theory and we have $F_{Br\beta}/F_{Br\alpha} = 0.565$, On the other hand, in the high-density limit in which the collisional process is dominant, assuming $T = 10000$ K as the gas temperature, we have $F_{Br\beta}/F_{Br\alpha} = 0.634$, which is the highest line ratio achievable with the collisional excitation but is lower than the observed values. Thus, in both the high density and low density limits, we cannot explain the high Brβ/Brα line ratio. We, hence, conclude that we cannot explain the anomaly only with the recombination and the collisional process in the optically thin cases.

4.3. Optically thick case

Another possibility is that one of the the Brackett lines becomes optically thick. In this case, it is possible to explain the high Brβ/Brα line ratio if the Brα line gets optically thick and saturated while the Brβ line is still optically thin.

In order to quantitatively investigate the Brβ/Brα line ratio, we use the Cloudy code (Ferland et al. 1998, ver. 10.00) and simulate the ratio in the optically thick case. Figure 3 shows the result of the Cloudy simulations of the Brβ/Brα line ratio. We find that the Brβ/Brα line ratio becomes high in the conditions with high local density (n) and large column density (N). The high Brβ/Brα line ratio is produced when the Brα line becomes optically thick, while the Brβ line is still optically thin. Figure 3 shows that the observed ratio in the three galaxies is explained in the conditions with $n \sim 10^8$ cm^{-3}, where the Brα line starts to become optically thick.

On the basis of this result, we conclude that, in order to explain the observed Brβ/Brα line ratio within ULIRGs, gas density as high as $n \sim 10^8$ cm^{-3} is required to achieve column density large enough to make the Brα line optically thick.

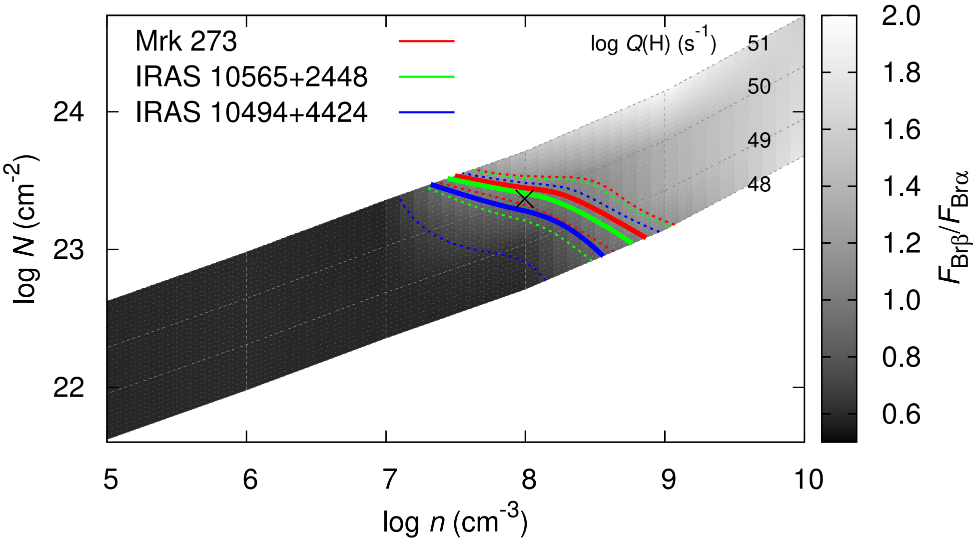

Figure 3. Cloudy result of the Brβ/Brα line ratio. Q(H) and n are varied within the ranges of 10^{48} s^{-1} $\leq Q(\mathrm{H}) \leq 10^{51}$ s^{-1} and 10^5 cm^{-3} $\leq n \leq 10^{10}$ cm^{-3} with the intervals of a decade. The Brβ/Brα line ratio is shown as the gray scale. The observed Brβ/Brα 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. The model calculated with $Q(\mathrm{H}) = 10^{50}$ s^{-1} and $n = 10^8$ cm^{-3} is indicated by the black cross.

4.4. **Implication**

The conditions indicated by our Cloudy simulation means that the ULIRGs with the anomaly line ratio harbor the high-density starburst with $n \sim 10^8$ cm^{-3}. Klessen et al. (2007) suggested that gas with a high temperature and a high density would yield a top-heavy initial-mass-function. An extreme case of the top-heavy IMF in the ultra-high-density starburst suggested by our results is expected to enhance the OB star population than normal conditions. We propose this scenario as an explanation of the high efficiency of starburst in ULIRGs.

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