Probing Star Formation in Ultraluminous Infrared Galaxies Using *AKARI* Near-Infrared Spectroscopy

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ABSTRACT

We carried out systematic observations of the H I recombination line Brα (4.05 μm) in nearby ($z < 0.3$) ultraluminous infrared galaxies (ULIRGs), using *AKARI* near-infrared 2.5–5.0 μm spectroscopy. We derived star formation rates (SFRs) from the Brα line, whose observed flux is predicted to be the highest among H I recombination lines in conditions with large dust extinction (visual extinction $A_V > 15$ mag) expected in ULIRGs. Using the 3.3 μm polycyclic aromatic hydrocarbon emission in addition to the Brα line as an indicator of the SFR, we estimated the contribution of the star formation to the total infrared luminosity in 51 ULIRGs. The contribution was on average 28±4 % in ULIRGs optically classified as H II, while 14±2 % in ULIRGs optically classified as LINER or Seyfert. This result indicates that the star formation is significantly active in H II ULIRGs and other energy source, i.e. active galactic nuclei, is needed in LINER ULIRGs.

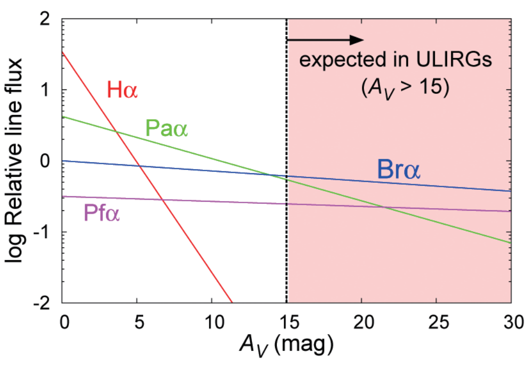
1. INTRODUCTION

Ultraluminous infrared galaxies (ULIRGs) radiate most ($\geq$ 90 %) of their extremely large luminosities ($> 10^{12}$ L$_\odot$) as infrared (IR) dust emission (Sanders et al. 1988). The possible energy source of their enormous IR luminosity is starburst activities and/or active galactic nuclei (AGN). Distinguishing their energy sources has been an important topic, but the large dust extinction makes it difficult to investigate this question.

To avoid the strong dust obscuration and investigate the energy sources of ULIRGs quantitatively, we focused on IR H I recombination line Brα (n : 5 → 4, 4.05 μm). As shown in Figure 1, the observed flux of the Brα line is predicted to be the highest among H I recombination lines (i.e. Hα or Paα lines) in conditions with large dust extinction (visual extinction $A_V > 15$ mag) expected in ULIRGs (e.g. Genzel et al. 1998). Thus the Brα line is the most suitable for probing star formation (SF) in ULIRGs. We systematically observed the Brα line in ULIRGs using *AKARI* and derived star formation rates (SFRs) so that the contribution of the SF to the IR luminosity was estimated.

2. OBSERVATION AND RESULTS

The observations were performed with the NG grism mode of the IRC spectrograph (Onaka et al. 2007) onboard the *AKARI* satellite (Murakami et al. 2007). Our targets were selected from the sources in the *AKARI* mission program "AGNUL" (P.I. T. Nakagawa). From AGNUL, we selected all 51 ULIRGs observed during the liquid-He cool holding period (2006 May 8 – 2007 Aug. 26). All targets were nearby ($z < 0.3$) objects. The data were processed through "IRC Spectroscopy Toolkit Version 20110114", the standard IRC-dedicated IDL toolkit. An example of obtained 2.5–5.0 μm spectra is shown in Figure 2(*Left*). The Brα line flux was estimated from integrating the best fit Gaussian. We succeeded in estimating the Brα line luminosity ($L_{\mathrm{Br}\alpha}$) in 35 ULIRGs.



line	n	λ (μm)	A_{line}/A_V
Hα	3→2	0.66	0.776
Paα	4→3	1.88	0.149
Brα	5→4	4.05	0.0356
Pfα	6→5	7.46	0.0020

Figure 1. Predicted fluxes of H I recombination lines versus visual extinction. The ordinate is normalized by the flux of Brα with no extinction. The theoretical line ratios in case B, T = 10000 K with low-density limit of Osterbrock & Ferland (2006) are assumed. The line extinction ratio A_{line}/A_V is taken from Draine (2003).

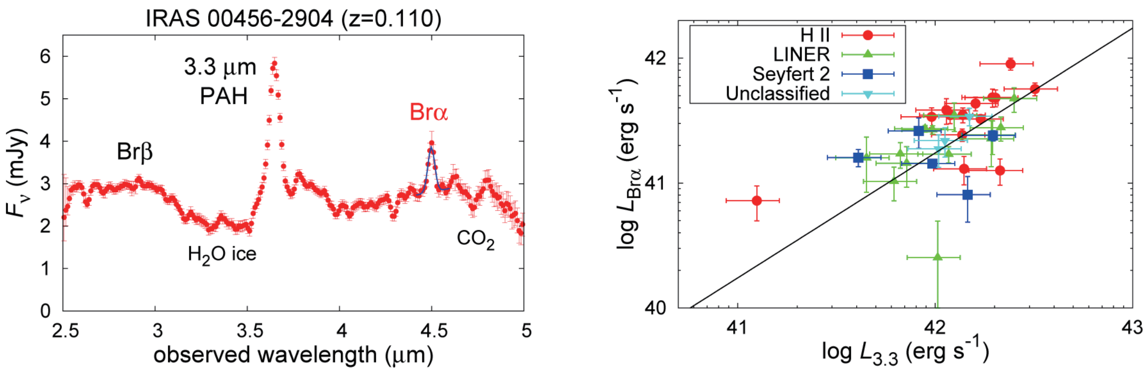


Figure 2. *Left panel*—example of *AKARI* 2.5–5.0 μm spectra. The best fit Gaussian profile used for calculating the Brα flux is shown by a blue solid line. *Right panel*— Comparison of Brα and 3.3 μm PAH luminosities. The solid line shows the regression line $L_{Br\alpha} = (0.174 \pm 0.003) L_{3.3}$.

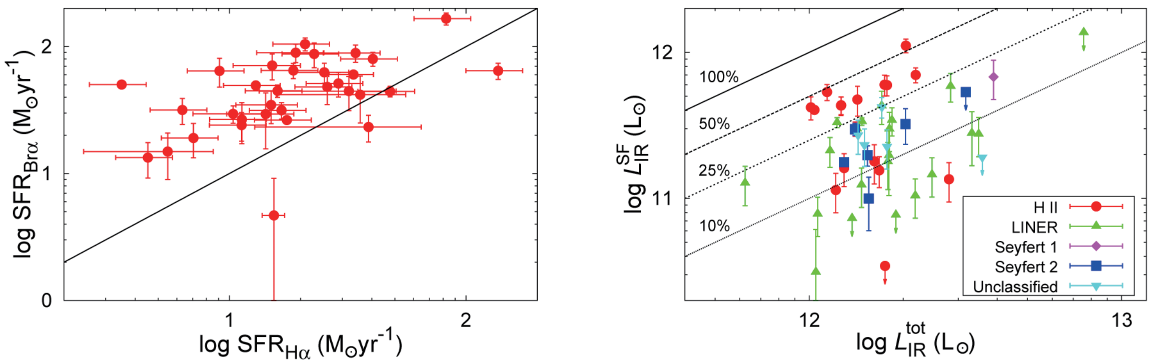


Figure 3. *Left panel*—comparison of SFRs derived from Brα and Hα. The solid line shows the one-to-one relation. *Right panel*—infrared luminosity derived from SFR versus actual infrared luminosity of the galaxy. The linear black lines indicate the SF contribution to the IR luminosity.

In the remaining objects, the Brα line was too faint to be detected, while the 3.3 μm polycyclic aromatic hydrocarbon (PAH) emission was observed. The 3.3 μm PAH emission also traces UV photons from OB stars and is stronger than the Brα line. However, complex emission mechanisms make it difficult to derive SFRs quantitatively from the luminosity of the 3.3 μm PAH emission ($L_{3.3}$). Therefore, we calibrated $L_{3.3}$ with $L_{Br\alpha}$ to derive SFRs in the objects with no Brα line detection. Figure 2(*Right*) shows a comparison of $L_{3.3}$ with $L_{Br\alpha}$. The $L_{3.3}$ were taken from Imanishi et al. (2008, 2010). Both $L_{Br\alpha}$ and $L_{3.3}$ were extinction corrected with Balmer decrement taken from the literature. They were well correlated with each other regardless of the optical classifications of the galaxies. From this result, we derived a relationship of $L_{Br\alpha} = (0.174 \pm 0.003) L_{3.3}$.

To calculate the SFRs from $L_{Br\alpha}$ (or $L_{3.3}$), we adopted the calibration provided by Murphy et al. (2011): SFR ($M_\odot$ yr^{-1})= 1.85×10^{-49} $L_{Br\alpha}$ (erg s^{-1}). Using this relation, we estimated SFRs in all our 51 targets.

3. DISCUSSION

3.1. Underestimation of SFRs in ULIRGs with Optical Observation

One of our motives of using the IR H I recombination line Brα was to reduce the effect of dust extinction and estimate the SFRs accurately. To verify this, we compared the SFRs obtained from the Brα line ($SFR_{Br\alpha}$) with those obtained from the optical Hα line ($SFR_{H\alpha}$). The Hα line fluxes were taken from the literature and extinction corrected with the Balmer decrement.

As shown in Figure 3(*Left*), $SFR_{Br\alpha}$ was systematically higher than $SFR_{H\alpha}$ (typically by a factor of 3), although the fluxes of the both lines were dust extinction corrected. This means the optical observation missed some fluxes originates from the heavily dust obscured regions and underestimated the SFRs. Using the Brα line, we now succeeded to reduce the effect of dust extinction.

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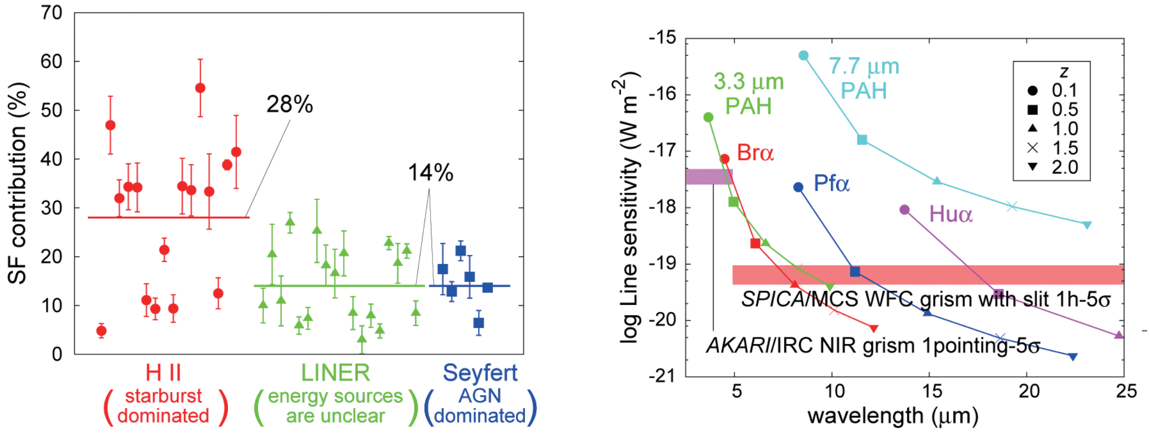

Figure 4. *Left panel*—SF contribution vs optical classification of galaxy. The solid lines indicate the averaged SF contribution in each classifications. *Right panel*—expected line fluxes in ULIRGs and sensitivity of *SPICA*/MCS. The fluxes of Brα and 3.3 μm PAH are the averaged value of this study. The fluxes of Pfα and Huα are calculated from Brα with case B. The flux of 7.7 μm PAH is estimated from the averaged value of Imanishi et al. (2007).

3.2. Contribution of Star Formation to the Infrared Luminosity

To estimate the contribution of SF to the IR luminosity, we converted SFRs to corresponding IR luminosities $L_{\rm IR}^{\rm SF}$ with the calibration provided by Murphy et al. (2011): SFR/(150 $M_\odot$ yr^{-1}) $\simeq L_{\rm IR}^{\rm SF}/(10^{12}\,L_\odot)$. Figure 3(*Right*) shows the comparison of $L_{\rm IR}^{\rm SF}$ with the total IR luminosity $L_{\rm IR}^{\rm tot}$. In all targets, $L_{\rm IR}^{\rm tot}$ was higher than $L_{\rm IR}^{\rm SF}$. This is consistent with the idea that $L_{\rm IR}^{\rm SF}$ represents the energy generated by SF, while $L_{\rm IR}^{\rm tot}$ corresponds to the total energy of the galaxy. We defined $L_{\rm IR}^{\rm SF}/L_{\rm IR}^{\rm tot}$ as the SF contribution.

We investigated the difference of the SF contribution among the optical classifications of galaxies. We found the SF contribution of the H II galaxies was systematically higher than that of LINERs or Seyferts (Figure 4 *Left*). The averaged value of the SF contribution was 28±4 % in H II galaxies and 14±2 % in LINERs and Seyferts. We performed the statistical t test and confirmed the difference between H II galaxies and LINERs/Seyferts is significant at the 99.7% level. This result indicates that SF is significantly active in H II galaxies and AGN is needed as the energy source in LINERs.

Using the IR H I recombination line Brα, we succeeded in estimating the energy sources of the nearby ULIRGs quantitatively regardless of the strong dust extinction.

4. PROSPECTS FOR *SPICA*

The high sensitivity of *SPICA*/MCS will enable us to apply our method to ULIRGs at higher redshift (Figure 4 *Right*). The higher-order H I recombination lines Pfα and Huα are observable at $z < 0.5$. If we calibrate the 7.7 μm PAH emission with the H I recombination lines, SFRs in ULIRGs at $z > 2.0$, where both SF and AGN activities are at their peak, could be studied.

This research is based on observations with *AKARI*, a JAXA project with the participation of ESA.

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