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THE BLUESHIFTED Paα BROAD LINE COMPONENT AND THE ORIGIN OF STRONG IRON EMISSION IN THE ULTRALUMINOUS INFRARED GALAXY IRAS 07598+6508

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ABSTRACT

We present the Paα emission profile of the ultraluminous infrared galaxy (ULFIRG) IRAS 07598+6508 which is an unusually strong Fe II emitter in the optical. The Paα emission line profile shows a blueshifted broad component (FWHM $\simeq$3900 km s^{-1}) together with a narrow core (FWHM$\leq$530 km s^{-1}). The presence of the broad line component strongly suggests that IRAS 07598+6508 has an active galactic nucleus, supporting a scenario of merger-induced quasar formation proposed by Sanders *et al.* [ApJ, 325, 74 (1988)], although we cannot rule out the possibility of a supernova-driven high speed wind. Possible detection of [Fe II]1.893 μm emission is also reported. It is shown that strong Fe II emitters such as IRAS 07598+6508 have intermediate *IRAS* color properties between normal quasars and cold ultraluminous infrared galaxies. We thus suggest an evolutionary link from cold ULFIRG through warm ULFIRG and Fe II ULFIRG to quasars.

1. INTRODUCTION

The *Infrared Astronomical Satellite (IRAS)* revealed a new class of active galaxies which emit most of their energy in the far infrared (FIR) region. In particular, much attention has been paid to ultraluminous ($L_{\rm FIR}\geq10^{12}L_\odot$) FIR galaxies (hereafter ULFIRGs) because their bolometric luminosities are comparable to those of quasars (Sanders *et al.* 1988a, 1988b). Since many of these ULFIRGs show evidence for mergers between galaxies, Sanders *et al.* (1988a, 1988b) proposed a new scenario that mergers between two gas-rich galaxies trigger formation of quasars, and that the warm [F(25 μm)/F(60 μm)>0.2] ULFIRGs represent a transition phase between cold ULFIRGs and optical quasars. IRAS 07598 +6508 is included in the warm ULFIRG sample. Low *et al.* (1988, 1989) made a survey of warm extragalactic objects [WEOs: F(25 μm)/F(60 μm)>0.25] in an area of 14 000 deg^2 and found 187 WEOs. Their spectroscopic studies showed that about 60% of the WEOs have active galactic nuclei including quasars, type 1 and type 2 Seyfert galaxies. IRAS 07598+6508 was also detected by their survey and it is classified as a quasar according to its stellar morphology.

Since the discovery of ULFIRGs, there has been a controversy concerning the origin of their huge luminosities that exceed $10^{12}L_\odot$. The intense FIR radiation presumably comes from dust grains heated by one or more of the following three energy sources: (1) super starbursts (Joseph *et al.* 1984; Rieke *et al.* 1985), (2) active galactic nuclei (DePoy *et al.* 1987; Sanders *et al.* 1988a, 1988b; Scoville *et al.* 1991), and (3) kinetic energy released by galaxy mergers (Harwit *et al.* 1987). Infrared and radio studies are more adequate to study the origin of the huge luminosity of the ULFIRGs because they are usually heavily obscured (cf. Becklin & Wynn-Williams 1987). In fact, near infrared spectroscopy has revealed hidden broad line regions in some ULFIRGs (DePoy *et al.* 1987; Nakajima *et al.* 1991a; Nakajima *et al.* 1991; Hines 1991).

IRAS 07598+6508 is one of warm ULFIRGs (Sanders *et al.* 1988b; Low *et al.* 1988) and is also known as one of the strongest Fe II emitters, whose optical spectrum is dominated by strong Fe II emission lines (Lawrence *et al.* 1988; Lipari *et al.* 1993; Kim & Sanders 1993). Therefore, IRAS 07598+6508 is the most interesting object among the ULFIRGs. In this paper, we report a discovery of the broad line component of Paα emission in IRAS 07598+6508 and discuss the origin of the huge luminosity of IRAS 07598 +6508. We also give comments on the origin of iron and its relation to the starburst–AGN connection.

2. OBSERVATIONS AND DATA REDUCTION

The observations were made with the Cryogenic Spectrometer (CRSP) on the 2.1 m telescope of Kitt Peak Na-

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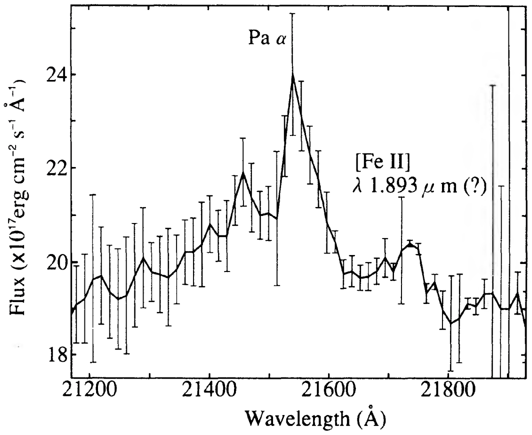

FIG. 1. Paα spectrum of IRAS 07598+6508.

tional Observatory on 1992 January 24. The CRSP is a long slit cooled grating spectrograph with a 62×58 SBRC InSb array detector. We used a 2.5″×81″ slit, giving a spatial scale of 1.5″ pixel^{-1}. Since the redshift of IRAS 07598+6508 is 0.1491 (Sanders *et al.* 1988b), the Paα emission ($\lambda_{\mathrm{Pa}\alpha}$=18571 Å in the rest frame) is observed in the *K* window. A 300 lines mm^{-1} grating was used in second order with a pixel resolution of 0.00133 μm pixel^{-1}. The actual spectral resolution was 530 km s^{-1} which was measured by using OH airglow emission lines.

The optical appearance of IRAS 07598+6508 is almost stellar (Sanders *et al.* 1988b). Thus we observed this galaxy with it being displaced along the slit by 10 arcsec between exposures. Each exposure time was 300 s. We obtained six exposures and thus the total integration time was 1800 s. The sky subtraction was made by image subtraction of one or two adjacent exposure frame(s). The flatfielding was performed by using dome flats taken at the beginning and the end of the observing night. A typical procedure of reduction of CRSP data was clearly given in Elston & Maloney (1990). The errors were estimated from the standard deviation in the sky, either side of the spectrum, in the coadded frames (see Hill *et al.* 1993).

A spectroscopic standard star BS 3569 (A7 IV; m_K=2.71 mag) was observed in order to calibrate the object spectra and to remove atmospheric absorption. Note, however, that the observing night was not photometric and the accuracy of the fluxes was estimated at about 20%. Using the image of the star along the slit, we estimated a seeing size of 2.5 arcsec. The wavelength calibration was performed by using the OH airglow emission lines of the sky frame which was made by a median average of the six frames.

3. RESULTS

3.1 The Paα Emission Profile

In Fig. 1, we show the nuclear spectrum of the Paα emission. This spectrum is extracted with an aperture of 2.5″×3.0″. This figure clearly shows the presence of a broad emission component together with the narrow peak. This narrow peak appears at λ=21547 Å, giving a redshift of 0.1491 which is just consistent with that derived from the optical spectroscopy (Sanders *et al.* 1988b). The broad emission appears to show a blueward asymmetry. In addition to the Paα emission, there are a few more narrow emission peaks.

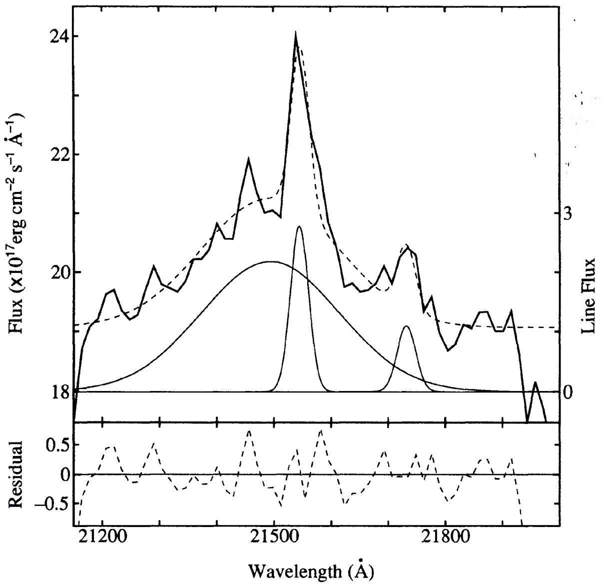

FIG. 2. The results of the Gaussian decomposition for the three components (the narrow and broad Paα and U1 line) is shown (see Table 1).

In order to estimate the contribution of both narrow and broad components, we have made a Gaussian decomposition of the Paα emission line. In this decomposition, we take account of the presence of one more narrow emission line at 21 732 Å because this feature seems to be real, and the similar emission has been observed in another ULFIRG, IRAS 14348−1447 (Nakajima *et al.* 1991a). We designate this unidentified line as U1. The result is shown in Fig. 2 and is summarized in Table 1.

The FWHM of the narrow Paα component is less than 530 km s^{-1}, which corresponds to the instrumental resolution, while that of the broad component amounts to 3910 km s^{-1}. The FWHM of the broad component is significantly larger than those of Hα (≃3000 km s^{-1}; Lawrence *et al.* 1988) and Hβ (2840 km s^{-1}; Sanders & Kim 1993). This difference may be attributed to the fact that the Paα emitting

TABLE 1. Results of 3-component fitting.

Component	λ_{obs} (Å)	λ_0 (Å)	Flux (erg cm^{-2} s^{-1})	Luminosity[1] (erg s^{-1})	FWHM[2] (km s^{-1})
Paα: Narrow	21545	18749	1.2×10^{-14}	5.2×10^{41}	< 530
Paα: Broad	21494	18705	7.3×10^{-14}	3.1×10^{42}	3910
U1[3]	21732	18712	5.0×10^{-15}	2.1×10^{41}	< 530

[1] The distance of IRAS 07598+6508 is assumed to be 596 Mpc (Sanders *et al.* 1989), which is estimated from the redshift using a Hubble constant of H_0=75 km s^{-1} Mpc^{-1}.

[2] The FWHMs are corrected for the instrumental broadening (530 km s^{-1}).

[3] Unidentified emission line.

TABLE 2. The emission linewidths of IRAS 07598+6508, other ULFIRGs, and radio galaxies.

Galaxy	Class[1]	Line	Component	FWHM (km s^{-1})	FWHM(Hα) (km s^{-1})	Ref. for NIR	Ref. for Hα
IRAS 07598+6508[2]	Warm	Paα	Narrow	<530		1	
		Paα	Broad	3900		1	
IRAS 14348−1447A	Cold[3]	Paα	Narrow	380±65		2	
		Paα	Broad	>2500		2	
IRAS 14348−1447B	Cold[3]	Paα	Narrow	520 ± 100		2	
		Paα	Broad	present		2	
IRAS 20460+1925	Warm	Paα	Single	2940±160	2500	3	
		Paα	Narrow	2500		3	
		Paα	Broad	3420±300		3	
IRAS 23060+0505	Warm	Paα	Single	2050	550	4	5
		Paα	Single	2900		3	
		Paα	Broad	4780[4]		3	
		Paβ	Single	1200		4	
Arp 220	Cold	Brα	Single	1300	607	6	7
		Brα	Narrow	1000		6	
		Brα	Broad	3300		6	
Cygnus A	NLRG	Paα	Single	510±60	500±100	8	9
3C 234	BLRG	Paα	Single	4300	890	10	11

[1] Warm=Warm ($F_{25\mu m}/F_{60\mu m}\geqslant 0.2$) ULFIRG, Cold=Cold ($F_{25\mu m}/F_{60\mu m}<0.2$) ULFIRG, NLRG=Narrow Line Radio Galaxy, and BLRG=Broad Line Radio Galaxy.

[2] The results of 3-component fitting (see table 1).

[3] The *IRAS* data are for the both system.

[4] The narrow linewidth of 550 km s^{-1} is assumed.

References: (1) This paper; (2) Nakajima *et al.* (1991); (3) Hines (1991): (4) Nakajima *et al.* (1991); (5) Hill *et al.* (1987); (6) DePoy *et al.* (1987); (7) Armus *et al.* (1989); (8) Ward *et al.* (1991); (9) Osterbrock & Miller (1975); (10) Carleton *et al.* (1984); (11) Grandi & Osterbrock (1978).

regions are more centrally concentrated than the Balmer emitting ones.

Next, we should like to mention that the broad Paα component is blueshifted with respect to the narrow one. The narrow Paα emission is blueshifted by $\simeq$700 km s^{-1}. The blue excess Paα emission was also observed in another ULFIRG, IRAS 23060+0505 (Nakajima *et al.* 1991b).

Finally, we comment on the U1 line. The rest wavelength of the U1 line is around 18 912 Å. This emission feature is also reported in the spectra of both components (the primary and the secondary nuclei) of IRAS 14348−1447 by Nakajima *et al.* (1991a). They suggested that this emission feature is Ca II $4s-(^1S)4p$ at 18 902 Å or H_2 $(1-0)$ $S(4)$ at 18 914 Å. Since, in IRAS 14348−1447, the expected H_2 $(1-0)$ $S(4)$ flux is too low to account for the observed flux, they favor the former case. In the case of IRAS 07598+6508, the rest wavelength more coincides with that of the H_2 line. However, there is no information on observations of other H_2 emission lines in this galaxy, thus we cannot conclude which is the better candidate. In addition to these two candidates, we propose other possibilities: [Fe II] $a^4D-a^4P(5-3)$ at 18 930 Å or [Fe II] $a^4F-a^4D(3-5)$ at 18 950 Å, emission lines (Nussbaumer & Storey 1988). Taking account of the similarity of wavelength, we consider that [Fe II] $a^4D-a^4P(5-3)$ at 18 930 Å is the most probable candidate. Since IRAS 07598+6508 shows the very strong optical Fe II emission lines (Lawrence *et al.* 1988; Lipari *et al.* 1993; Kim & Sanders 1993), we will have to take account of these cases in future studies.

3.2 Spatial Extent of the Emitting Region

The spatial extent is examined using the slit profile. Both the continuum and the Paα emission regions have the same width as that of the seeing size (2.5 arcsec in FWHM). This is consistent with the stellar like morphology in the optical observation (Sanders *et al.* 1988b).

4. DISCUSSION

4.1 A Comparison with Other NIR Spectroscopy of ULFIRGs

Prior to this work, the broad components of hydrogen recombination lines have been detected in the following five ULFIRGs: Arp 220 (Brα; DePoy *et al.* 1987), IRAS 14348 −1447A and B (Paα; Nakajima *et al.* 1991a), IRAS 20460 +1925 (Paα; Hines 1991), and IRAS 23060+0505 (Paα and Paβ; Nakajima *et al.* 1991b; Paα; Hines 1991). These detections are summarized in Table 2 together with the observations of the radio galaxies 3C 234 (Carleton *et al.* 1984) and Cygnus A (Ward *et al.* 1991). Although the number of the observed galaxies listed in Table 2 is so small, there is a tendency that the warm ULFIRGs show the *unambiguous* broad line components.

Thompson (1992) reported the NIR spectroscopy of six low redshift ($z\simeq0.08-0.16$) quasars and showed that the Paα widths are nearly the same as those of Hα emission lines, ranging from 1600 to 3200 km s^{-1}. Since the broad Paα emission lines detected in the ULFIRGs are just comparable to those of quasars, we may conclude that IRAS 07598 +6508 and the other ULFIRGs with the unambiguous broad line component listed in Table 2 have AGNs in their nuclei.

One more possible explanation for the broad line component in IRAS 07598+6508 is the high speed wind generated by bursts of supernova events near the nuclear region (Heckman *et al.* 1990; Terlevich 1992). As noted before, IRAS 07598+6508 is one of the strongest Fe II emitters (Lipari *et al.* 1993 and references therein). The abundant iron is generally considered to be expelled from supernova explosions (see Sec. 4.4). Further, our broad line component is blueshifted with respect to the narrow one. This characteristic is ubiquitously observed in the strong Fe II emitters (Boroson & Meyers 1992) and in some starburst nucleus galaxies (Taniguchi 1987).

Here we make rough estimates of the required supernova rate (SNR) and star formation rate (SFR) to account for the luminosity of the broad Paα emission. The observed Paα luminosity of the broad component is 3.1×10^{42} erg s^{-1} (see Table 1). This luminosity gives an ionized gas mass of $\mathscr{M}_{\rm gas}=8.4\times10^{7}\mathscr{M}_\odot$ in the case of an electron density $N_{\rm e}=10^3$ cm^{-3} (a typical value of nuclear H II regions: Kennicutt *et al.* 1989). Adopting a wind velocity of 2000 km s^{-1} (about a half of FWHM of the broad line component), we obtain a kinetic energy of $E_{\rm kin}\simeq3.4\times10^{56}$ erg. The kinetic energy released from one Type II SN is 10^{51} erg. If we assume an efficiency of wind luminosity to kinetic energy, $\sim$0.1 (Dyson & Williams 1980), we need 3.4×10^6 Type II SN events. Since, further, these supernova explosions should occur almost simultaneously, if we adopt the lifetime of one SN of $\tau_{\rm SN}=10^4$ yr the SNR is estimated at 340 SN yr^{-1}. The number of Type II supernova events is roughly equal to that of stars with several solar masses. Thus, adopting a mass of $5\mathscr{M}_\odot$, we obtain a SFR of $1700\mathscr{M}_\odot$ yr^{-1} as a lower limit. On the other hand, the SFR estimated from the FIR luminosity (cf. Hunter *et al.* 1986) is about $730\mathscr{M}_\odot$ yr^{-1}, which is significantly smaller than the above value. Although we cannot rule out entirely the possibility of the supernova-driven broad line emission because there are some uncertainties in the above estimate ($N_{\rm e}$, $\tau_{\rm SN}$, the fraction of the kinetic energy deposited to the ambient gas, etc.), very fine tuning (mostly simultaneous SN explosions) would be necessary to account for the kinetic energy of the broad line component.

4.2 Extinction

It is important to consider how large is the extinction because the ULFIRGs, including IRAS 07598+6508, are considered to be dust-enshrouded quasars (Sanders *et al.* 1988a, 1988b). Here we estimate the extinction using both the Paα emission and the published Hβ data (Lipari *et al.* 1993; Kim & Sanders 1993).

Lipari *et al.* (1993) only gives an equivalent width of Hβ emission [EW(Hβ)=44 Å). Measuring the continuum flux at the Hβ emission ($\simeq3\times10^{-15}$ erg cm^{-2} s^{-1} Å^{-1}) in Fig. 1 of Lipari *et al.* (1993), we obtain the Hβ flux, $I_{\rm H\beta}\simeq1.3\times10^{-13}$ erg cm^{-2} s^{-1}. On the other hand, we obtain $I_{\rm H\beta}\simeq1.2\times10^{-13}$ erg cm^{-2} s^{-1} from the nuclear (central 2 arcsec regions) spectrum by Kim & Sanders (1993), which is almost the same as that of Lipari *et al.* (1993). In this estimate, we have made a deblending of the Hβ emission under the assumption that the Hβ emission is contaminated by the Fe II emission lines [Fe II(30) at 4825.7 Å and Fe II(42) at 4923.9 Å]. Since the iron emission lines are almost comparable to or stronger than the Hβ emission, there is difficulty in the deblending. It is, however, reasonable to adopt an Hβ flux of $I_{\rm H\beta}\simeq1.2\times10^{-13}$ erg cm^{-2} s^{-1} in the following discussion because the two independent analyses by us and Lipari *et al.* (1993) give nearly the same results.

We compare this Hβ flux with that of the Paα emission observed by us. The linewidth of the Hβ emission is 2840 km s^{-1} (estimated from the data of Kim and Sanders), being comparable to that of the broad Paα emission. Therefore, we use the total (the narrow+the broad) flux given in Table 1. In this way, we obtain a Paα to Hβ intensity ratio of $I_{\rm Pa\alpha}/I_{\rm H\beta}=0.711$ while the theoretical value is 0.343 (Case B, $T_{\rm e}=10^4$ K and $N_{\rm e}=10^4$ cm^{-3}: Osterbrock 1989). Comparing the observed and the theoretical Paα/Hβ ratio, we estimate $A_V=0.75$ mag. This value is consistent with typical ones estimated for BLRs of many AGNs (cf. Ward *et al.* 1987).

Large extinction around 50 mag has been reported in many ULFIRGs based on the observations of the Brα/Brγ ratio and/or the silicate absorption feature at 9.7 μm (Becklin & Wynn-Williams 1987). Further, the unusually large column density of molecular gas in some ULFIRGs such as Arp 220 nominally gives $A_V\simeq1000$ mag (Scoville *et al.* 1991). In IRAS 07598+6508, much molecular gas has been detected ($6.3\times10^{10}\mathscr{M}_\odot$: Sanders *et al.* 1989). If we assume that the molecular gas is highly concentrated in the central 5 kpc region, as is usually observed in most of the ULFIRGs (Scoville *et al.* 1991), the molecular gas surface density would be $3.2\times10^{3}\mathscr{M}_\odot$ pc^{-2}. This surface density nominally gives $A_V\simeq400$ mag in IRAS 07598+6508.

4.3 Origin of the Huge Luminosity of IRAS 07598+6508

Since the most important issue related to the ULFIRGs is the origin of their huge luminosities, our discussion is mainly addressed to this problem in this subsection. There has been a controversy concerning the origin of their huge luminosities since their discovery (cf. Joseph *et al.* 1984; Rieke *et al.* 1985; DePoy *et al.* 1987; Sanders *et al.* 1988a, 1988b; Mouri & Taniguchi 1992). The major ideas are a super starburst, a hidden AGN, or both. After summarizing some interesting observational properties of IRAS 07598+6508, we consider which energy source is more favored in this galaxy.

Recently, Kobayashi *et al.* (1993) reported their low-resolution NIR spectrophotometry of fourteen nearby ($z<0.3$) quasars including IRAS 07598+6508. They showed that the observed NIR continua of all the objects are described with a combination of power-law and black body radiation. IRAS 07598+6508 has no peculiar continuum and its spectrum is almost similar to those of the rest of the quasars. This suggests the presence of an AGN in IRAS 07598+6508.

Neff & Hutchings (1992) made a radio continuum map at $\lambda=6$ cm and showed that IRAS 07598+6508 has an unresolved ($\leqslant0.8''$, corresponding to 2.3 kpc) radio core with some extended radio emission. While the extended radio emission may be considered to be related to circumnuclear star formation, the presence of the radio core supports the AGN picture. Recently, Condon *et al.* (1991) presented a model of a compact starburst in the nuclear region to explain the unusual nature of ULFIRGs which have both blackbody-like FIR colors and unresolved radio cores. However, the FIR color of IRAS 07598+6508 cannot be explained

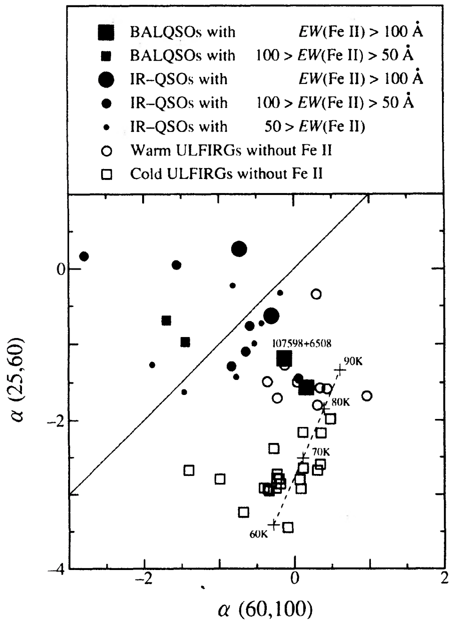

FIG. 3. The *IRAS* color diagram for IR-selected quasars, low-ionization BALQSOs, warm and cold ultraluminous infrared galaxies (see text). The solid line represents the colors of pure power-law spectra and the dashed line shows those of black body with indicated temperatures.

with a single black body spectrum (see Fig. 3). Further, the observational nature of IRAS 07598+6508 is similar to that of Mrk 231 (one of warm ULFIRGs) in many respects (e.g., FIR colors, strong optical Fe II emission, and the presence of radio core). Mrk 231 has been considered to be the most probable candidate for a hidden AGN among the ULFIRGs (cf. Condon *et al.* 1991). It is therefore more likely to consider that the radio core represents evidence for the AGN in IRAS 07598+6508.

Here, we consider whether or not the AGN is able to account for all the huge luminosity of IRAS 07598+6508 [$L_{\rm FIR}(8–1000\ \mu{\rm m})=2.8\times10^{12}L_\odot$ and $L_{\rm bol}=5.6\times10^{12}L_\odot$; Sanders *et al.* 1988b]. The presence of extended radio emission (Neff & Hutchings 1992) shows that IRAS 07598+6508 may have circumnuclear star forming regions. Namely, there is still a possibility that a part of the narrow Paα emission comes from a *putative* nuclear starburst. The luminosity of the narrow Paα emission is 5.2×10^{41} erg s^{-1} (see Table 1). Since the theoretical Paα/Hα intensity ratio for Case B is 0.12 (Osterbrock 1989), the Hα luminosity is estimated at 4.3×10^{42} erg s^{-1}, giving the number of Hα photons of 1.4×10^{54} s^{-1}. Since 2.2 ionizing photons produce one Hα photon, we obtain the number of ionizing photons of 2.9×10^{54} s^{-1}. Since the number of ionizing photons emitted by O5 and B0 stars are 4.68×10^{49} s^{-1} and 4.68×10^{47} s^{-1}, respectively (Osterbrock 1989), we obtain that the required numbers of O5 or B0 stars are 6.2×10^4 or 6.2×10^6 stars, respectively. The luminosities of these stars amount to $3.1\times10^{10}L_\odot$ and $1.2\times10^{11}L_\odot$ for O5 and B0 stars, respectively. In either case, massive stars *nominally* contribute about only 2% of the bolometric luminosity.

In the above estimates, we do not consider the effect of extinction. Unfortunately, there is no direct information about the extinction in IRAS 07598+6508. If the massive stars account for the observed bolometric luminosity of IRAS 07598+6508, the extinction should recover a factor of 50. This factor is equivalent to the extinction of 4.3 mag at $\lambda_{{\rm Pa}\alpha}$, corresponding to $A_V\simeq26$ mag. Although this value is not significantly large for the ULFIRGs (Becklin & Wynn-Williams 1987; Scoville *et al.* 1991), the observed Paα/Hβ emission line ratio only gives an extinction of 0.75 mag. Therefore, at present, it is unlikely to consider that the starburst activity solely accounts for a significant amount of the bolometric luminosity of IRAS 07598+6508.

On the other hand, the presence of the broad Paα component strongly suggests that IRAS 07598+6508 has an AGN. The broad Paα luminosity amounts to 3.1×10^{42} erg s^{-1}, giving a Hα luminosity of 2.6×10^{43} erg s^{-1} (Paα/Hα=0.12). Ward *et al.* (1988) studied *IRAS* selected AGNs and showed that the infrared to Hα luminosity ratio is 2.04 ± 0.55 in logarithm for about 40 AGNs.[2] Using the relation given by Ward *et al.* (1988), we obtain an expected value of $L_{\rm IR}=2.8\times10^{45}$ erg s^{-1} for IRAS 07598+6508 while the *IRAS* 25 and 60 μm fluxes actually give $L_{\rm IR}=6.9\times10^{45}$ erg s^{-1}. Therefore, the AGN inferred from the broad line emission accounts for 40% of the bolometric luminosity of IRAS 07598+6508. Taking account of the measurement error of the Paα emission, we may conclude that the major energy source in IRAS 07598+6508 is the AGN itself.

4.4 Origin of Iron and its Relation to the Starburst–AGN Connection

Finally, we comment on the origin of abundant iron and its relation to the starburst model of AGN (Terlevich & Melnick 1985; Terlevich *et al.* 1992). Among the original ULFIRGs by Sanders *et al.* (1988a, 1988b), only two galaxies (IRAS 07598+6508 and Mrk 231) show the strong optical Fe II emission features (cf. Lipari *et al.* 1993). Recently, Boroson & Meyers (1992) published optical properties of infrared-color selected ($S_{25\mu{\rm m}}/S_{60\mu{\rm m}}>0.25$: almost comparable to the definition of warm ULFIRGs) quasars (hereafter IR quasars) as an extension of the studies of Low *et al.* (1988, 1989). Their optical spectra show that almost all the IR quasars have Fe II emission features.

In order to elucidate the FIR nature of IRAS 07598+6508 and other related objects, we show an *IRAS* two color diagram in Fig. 3. Here, we use color indices $\alpha(\lambda_1,\lambda_2)=-\log(S_{\lambda_1}/S_{\lambda_2})/\log(\lambda_1/\lambda_2)$. In the class of ULFIRG, we add southern ULFIRGs studied by Melnick & Mirabel (1990), most of which are cold ULFIRGs. Note that IRAS 07598+6508 is designated as a low-ionization broad absorption line (BAL) quasar (cf. Boroson & Meyers 1992). In this diagram, there is a tendency that warm ULFIRGs and strong Fe II emitters including IRAS 07598+6508 are located in the intermediate region between IR quasars and cold ULFIRGs, suggesting an evolutionary link from cold

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[2] Note that the infrared luminosity is defined as $L_{\rm IR}=F_{25\mu{\rm m}}\times\nu_{25\mu{\rm m}}+F_{60\mu{\rm m}}\times\nu_{60\mu{\rm m}}$ in Ward *et al.* (1988).

ULFIRGs through warm ULFIRGs to quasars (Sanders *et al.* 1988b).

The most important point is that the strong Fe II emitters cannot be seen in the cold ULFIRGs. This may be curious because the cold ULFIRGs show evidence for intense star formation manifested by their huge FIR luminosities themselves (cf. Majewski *et al.* 1993) and thus it would be expected that many supernova explosion events occurred in them. Namely, we have to answer the question: why do the strong Fe II emitters favor the warm ULFIRGs and quasars rather than the cold ones? This problem may be related to the origin of iron. The major contributor of iron in starburst systems such as ULFIRGs may be considered to be Type II SNe because the mass function in the starburst is top heavy (i.e., high-mass star enhanced star formation). However, if this is the case, we cannot explain why the cold ULFIRGs show no detectable Fe II emission.

It is known that iron arises mainly from Type Ia supernovae (60% of iron) while Type II SNe also contribute to the iron abundance up to about 30% in interstellar matter of the ordinary environment in galaxies. It has been usually considered that the iron pollution by Type Ia SNe needs about one Gyr. The time scale of mergers depends on the orbital parameters of mergers; 0.6 Gyr for prograde orbits and 1.2 Gyr for retrograde ones (cf. Noguchi 1991; Barnes 1992). The majority of the warm ULFIRGs may experience retrograde mergers according to their tidal features. It is therefore considered that the time scale of mergers in the warm ULFIRGs is almost comparable to that of iron pollution from Type Ia SNe if low mass star formation (stars with a few solar masses which are the major progenitors of Type Ia SNe) as well as high mass star formation would be enhanced at the onset of the first attack in the merger events. If this is the case, we would expect the Type Ia SNe burst in the final phase of the mergers.

Recently, Ishimaru *et al.* (1993) showed that the iron pollution from Type Ia SNe takes a much longer time, i.e., 2.5 Gyr, analyzing the [O/Fe] vs [Fe/H] relation and metallicity distribution of long-lived disk stars in the solar neighborhood of our galaxy. This time scale seems to be significantly longer than that of merging events. However, all the strong Fe II emitters in mergers have stellar-like morphology (e.g., IRAS 07598+6508) or very faint tidal tails (e.g., Mrk 231). This means that these galaxies are actually in a late phase of mergers. The time scale of mergers quoted above corresponds to that for the merger of two galactic nuclei. In this phase, tidal features may not vanish at all. Therefore, the ages of mergers with little tidal features are probably longer than one Gyr and thus we cannot rule out that the iron in mergers is attributed to Type Ia SNe.

One problem remains here for a Type Ia origin of iron. It is usually considered that starburst phenomena have top-heavy mass functions and thus it is unlikely to form a large number of low mass stars in starbursts (cf. Rieke 1991). Based on near- and mid-infrared photometry, Wright *et al.* (1988) showed that a probable lower mass limit is $3-6\mathscr{M}_\odot$ in most starbursts. On the other hand, the mass of progenitors of Type Ia SNe is $1.7-2\mathscr{M}_\odot$, depending on the metal abundance. This is the lowest case because we assume an age of 2.5 Gyr following the recent study of Ishimaru *et al.* (1993). However, Wright *et al.* (1988) also reported that there are a few exceptions including one of the well-known merger, NGC 6240. In this galaxy, they cannot constrain the lower mass limit. Although this fact is not applied to all the mergers, it is possible to consider that the star formation in mergers is different from that in usual starbursts in galactic nuclei. In fact, Mouri & Taniguchi (1992) showed that the most massive stars in mergers are systematically less massive than those in usual starbursts that occur in nuclei of disk galaxies.

The final question is how the presumed supernova events are related to nuclear activity in ULFIRGs and quasars. It is at least acceptable that supernova events have polluted the circumnuclear environment in some warm ULFIRGs and quasars. This argument has a two-fold explanation. One is that the strong Fe II emission and some broad emission lines can be attributed to the supernova explosions themselves. This idea corresponds to the starburst-warmer scenario proposed by Terlevich and his collaborators (cf. Terlevich & Melnick 1985; Terlevich *et al.* 1992). This possibility is also discussed by Lipari *et al.* (1993). The other possibility is that iron-polluted interstellar matter due to Type Ia SNe is heated by nonthermal radiation from AGN. This idea needs no starburst engine. In order to settle this problem, extensive studies would be desirable for many ULFIRGs and quasars with Fe II emission as suggested by Lipari *et al.* (1993). Hard x-ray spectroscopy would be helpful to the discrimination between these two ideas.

5. CONCLUSIONS

In this paper, we have reported the discovery of a broad line component in the Paα emission in one of the warm ULFIRGs, IRAS 07598+6508. Our main results and conclusions are summarized below.

(1) The Paα emission line profile of IRAS 07598+6508 shows a blueshifted broad component (FWHM$\simeq$3900) together with a narrow core (FWHM$\leqslant$530 km s^{-1}). The linewidth of this broad component is comparable to those of quasars. It is therefore strongly suggested that IRAS 07598+6508 has an active galactic nucleus, supporting a scenario of merger-induced quasar formation proposed by Sanders *et al.* (1988a, 1988b).

(2) We detected an emission line around 18 912 Å (rest frame wavelength). This emission feature was also reported in the spectra of both components (the primary and the secondary nuclei) of IRAS 14348−1447 by Nakajima *et al.* (1991a). Although they suggested that this emission is attributed to Ca II $4s-(^1S)4p$ at 18 902 Å or H_2 (1−0) $S(4)$ at 18 914 Å, we propose another possibility of [Fe II] $a^4D-a^4P(5-3)$ at 18 930 Å taking account of the fact that IRAS 07598+6508 shows very strong Fe II emission lines in its optical spectrum.

(3) It is shown that strong Fe II emitters such as IRAS 07598+6508 have intermediate *IRAS* color properties between normal quasars and warm/cold ultraluminous infrared galaxies. We thus suggest that the strong Fe II emitters may be an evolutionary link between quasars and ultraluminous

infrared galaxies. The proposed sequence is; cold ULFIRG→warm ULFIRG→Fe II quasar→quasar. The BAL phase may be associated with the Fe II phase as well.

(4) It is at least acceptable that supernova events enriched iron in the circumnuclear environment in some warm ULFIRGs and quasars. Comparing the time scales between merger events and iron pollution from stars, we suggest that the major iron contributor is Type Ia supernovae even in these ULFIRGs.

(5) It is still uncertain how the SN explosions are related to the nuclear activity in these AGNs. Although it is possible to consider that some broad emission lines can be attributed to the supernova explosions themselves, it is also possible that iron-polluted interstellar matter due to Type Ia SNe is heated by nonthermal radiation from the central engine.

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