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IRAS 02366−3101: AN ACCRETION DISK CANDIDATE AMONG LUMINOUS *IRAS* GALAXIES

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ABSTRACT

In this *Letter* we present the detection, for the first time, of double-peaked broad Balmer Hα and Hβ emission-line profiles in a luminous *IRAS* galaxy: IRAS 02366−3101 with log $L_{\rm FIR} = 10.94\ L_\odot$.

These double-peaked broad emission-line profiles consist of three components characterized by the following mean parameters: (1) a narrow component with FWHM = 571 km s^{-1}, (2) a blueward broad component with FWHM = 2794 km s^{-1} and velocity shift of the peak of −2120 km s^{-1}, (3) a redward broad component with FWHM = 2614 km s^{-1} and velocity shift of the peak of +2911 km s^{-1}, and (4) a blueward broad–to–redward broad emission-peak ratio of around 1.2. These parameters are consistent with the emission-line profile predicted by models such as those of Chen and Halpern, where the low-ionization line emission comes from a relativistic accretion disk around a supermassive black hole.

This detection shows that IRAS 02366−3101 is a candidate to host an accretion disk around a supermassive black hole in its nucleus, although other alternatives cannot be ruled out.

Subject headings: accretion — galaxies: individual (IRAS 02366−3101) — quasars

1. INTRODUCTION

During the last three decades considerable theoretical and observational effort has been devoted to understanding the nature of the source of energy in active galactic nuclei (AGNs). In the last several years, two main energy sources have been proposed: (*a*) gravitational, where the energy is emitted by a hot accretion disk circling a central massive black hole (Rees 1984, and references therein); and (*b*) starburst, where violent star formation processes occur in high-metallicity environments (Terlevich & Melnick 1985, and references therein). At the same time, we have firm evidence that nuclear activity in galaxies and star formation activity in the inner region can be triggered by galaxy interactions (see review by Heckman 1990). Theories have also been proposed that link the starburst and the black hole models (Weedman 1983; Norman & Scoville 1988).

The investigations related to the nature of high-luminosity ($L_{\rm IR} \geq 10^{11}\ L_\odot$) and ultraluminous infrared galaxies ($L_{\rm IR} \geq 10^{12}\ L_\odot$), have become a key area in AGN research for the following reasons.

1. Virtually all luminous *IRAS* galaxies have also been shown to be extremely rich in interstellar gas (predominantly molecular hydrogen), highly concentrated in their nuclei (Scoville & Soifer 1991). This interstellar medium plays a central role, providing a dissipative medium for galactic collisions, promoting star formation, and possibly fueling accretion onto a compact object (Scoville et al. 1991).

2. Imaging surveys, for different samples of ultraluminous galaxies, show that 100% are in interacting systems (Sanders et al. 1988; Melnick & Mirabel 1990).

3. The luminous infrared galaxies are the dominant population of objects in the local universe (Soifer et al. 1987).

4. There is increasing evidence that luminous IR galaxies may represent an early phase in the evolution of the activity in galaxies (Sanders et al. 1988; Hutchings & Neff 1988, 1991).

Most studies based on the emission-line rates and Hα or IR luminosities (Armus, Heckman, & Miley 1989; Leech et al. 1989; Lipari, Bonatto, & Pastoriza 1990) suggest that luminous *IRAS* galaxies are places where an active star formation process is taking place. Extraordinary large star formation rates, amounting up to a few hundred solar masses per year, and winds with velocities of the order of 500 km s^{-1}, have recently been invoked to explain the double-peaked narrow-line profiles, the emission-line ratios, and the energy budget in high-luminosity *IRAS* galaxies (Heckman, Armus, & Miley 1990).

Moreover, specific models to explain the emission-line profiles, the line ratios and the Hα luminosity in the Superantennae (Colina, Lipari, & Macchetto 1991a) show the need, under certain assumptions, of an intense ongoing star formation process together with the existence of a hidden quasar-like source in the center of that ultraluminous galaxy. This is consistent with the hypothesis of Sanders and collaborators (Sanders et al. 1988) that all ultraluminous galaxies are dust-obscured quasars and with the detection of broad Paschen-alpha emission lines in two luminous *IRAS* galaxies with a Seyfert type II optical spectrum (Hines 1991). Similar obscuration effects have also been detected in Seyfert II galaxies like IC 5063 (Colina, Sparks, & Macchetto 1991b and references therein).

Since the detection of quasars almost 30 years ago, central supermassive black holes and accretion disks around them have been hypothesized as the ionizing source located at the center of any active galaxy.

Detections of double-peaked broad emission-line profiles have been made in a number of active galaxies ranging from low-luminosity AGNs (Arp 102B: Chen, Halpern, & Filippenko 1989; Miller & Peterson 1990) to radio galaxies (3C 390.3: Pérez et al. 1988; Veilleux & Zheng 1991; 3C 332: Halpern 1990) and luminous QSOs (OX 169: Stockton & Farnham 1991). Such emission-line profiles have recently been

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invoked as evidence of an accretion disk around a massive black hole.

Theoretical calculations by different groups (Chen & Halpern 1989; Dumont & Collin-Souffrin 1990) suggest that a large fraction of the broad low-ionization emission lines could be generated in the accretion disk itself, and therefore a double-peaked emission-line profile should be expected under certain restrictions concerning the physical parameters involved. However, alternative models invoking double-stream BLRs (Robinson, Pérez, & Binette 1990) or even a binary system of supermassive black holes (Stockton & Farnham 1991) could also produce a double-peaked broad emission-line profile.

IRAS 02366−3101 is a luminous *IRAS* galaxy located at a redshift $z = 0.0629$. Using the prescription as given in Catalogued Galaxies in the *IRAS* Survey (Version 2, 1989), it has a far-infrared luminosity of $\log L_{\rm FIR} = 10.94\ L_{\odot}$, and it was detected in the survey of southern warm *IRAS* AGN candidates (Lipari et al. 1990; Lipari, Macchetto, & Golombek 1991a). Its far-infrared spectral energy distribution with $\alpha(60, 25) = -1.13$ and $\alpha(100, 60) = -1.4$ is similar to that found in *IRAS*-selected Seyfert 1 galaxies (Miley, Neugebauer, & Soifer 1985). Its optical morphology shows a ring structure around the main body of the galaxy (see Fig. 1 [Pl. L3]) similar to that found in the nearby quasar MR 2251−178 (Macchetto et al. 1990) or in the luminous *IRAS* galaxies IRAS 09595−0755 (Wakamatsu & Nishida 1987), IRAS 02321−0900 (Rodriguez-Espinosa & Stanga 1990), and IRAS 0559−5756 (Lipari et al. 1991b). This morphology would most likely be the consequence of a collision with a companion galaxy.

In this *Letter* we present the detection for the first time, of double-peaked broad Hα and Hβ emission-line profiles in IRAS 02366−3101 and therefore, in a luminous *IRAS* galaxy. A discussion of the results in terms of accretion disk models and alternative models is presented. The characteristics of this galaxy are also compared with those of other accretion disk candidates. Throughout the *Letter*, a Hubble constant of $H_0 = 75$ km s^{-1} Mpc^{-1} will be assumed.

2. OBSERVATIONS AND REDUCTIONS

The spectroscopic observations of IRAS 02366−3101 reported in this work were obtained with the "Z-machine" (Tonry & Davis 1979; Latham 1982; da Costa et al. 1984) attached to the Cassegrain spectrograph at the 2.15 m Ritchey-Chrétien telescope of CASLEO, San Juan, Argentina. The data were obtained during four photometric nights in 1989 November.

The observations were made using the instrumental configuration and technique described in previous papers of the survey of southern warm *IRAS* AGN candidates giving a dispersion of 120 Å mm^{-1}, an effective resolution of 5 Å, and covering the wavelength range 4600–7300 Å.

The spectra were flux calibrated with stars from the catalog of "Southern Spectrophotometric Standards" (Stone & Baldwin 1983). Each spectrum was corrected for redshift separately. In order to increase the signal-to-noise ratio, the corrected spectra were later averaged for the final detailed study. The IRAF package at the STScI was used to measure the spectra. The emission lines were decomposed using Lorentzian profiles by means of a nonlinear least-squares algorithm described in Bevington (1969); the convergence criterion was the minimization of the reduced chi-square.

3. RESULTS

The emission-line spectrum of IRAS 02366−3101 (Fig. 2*a*), shows a quasar-type spectrum with the broad recombination emission lines showing a double-peaked line profile. This is particularly clear in Hα where we can distinguish a narrow component together with two broad components (see Fig. 2*b*). The spectral region comprising Hα, the [N II] emission lines at λ6548 and λ6584, and the [S II] emission lines at λ6717 and λ6732 was fitted using seven components and a continuum level for the spectral region from λ6400 to λ6750. The five narrow components corresponding to narrow Hα, [N II], and [S II] emission lines were subtracted afterward, and the result, representing the double-peaked Hα emission-line profile, was smoothed using a filter in order to improve the signal-to-noise ratio while preserving the line profile parameters (see Fig. 3). The result of the best fit showing the parameters corresponding to each of the Hα line components and the [N II] λ6584 line is presented in Table 1. The broad emission-line profile consists of two components with velocity shifts $V_{\rm blue} - V_{\rm sys} = -2089$ km s^{-1} and $V_{\rm red} - V_{\rm sys} = +2907$ km s^{-1}, respectively, while

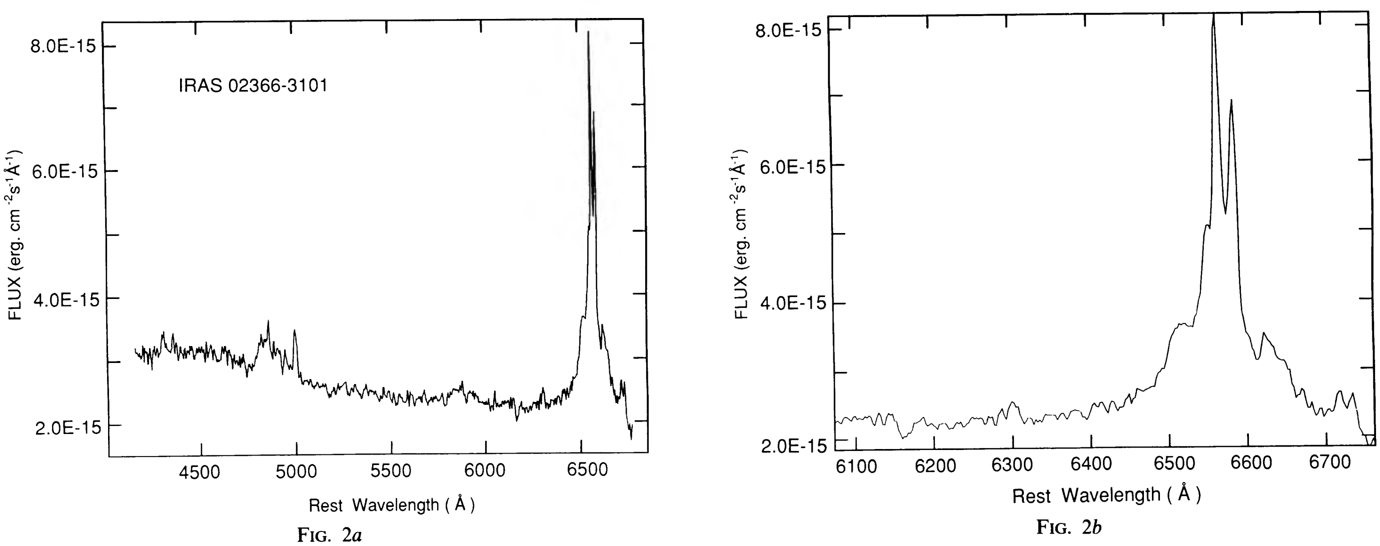

FIG. 2.—(*a*) Spectrum of IRAS 02366−3101 showing the spectral region from Hγ up to [S II] $\lambda\lambda$6717, 6731. The broad emission lines show substructure with the double-peaked profile. (*b*) Expansion of the previous figure around the Hα, [N II] $\lambda\lambda$6548, 6584 and [S II] $\lambda\lambda$6717, 6731 lines showing in detail the line profiles.

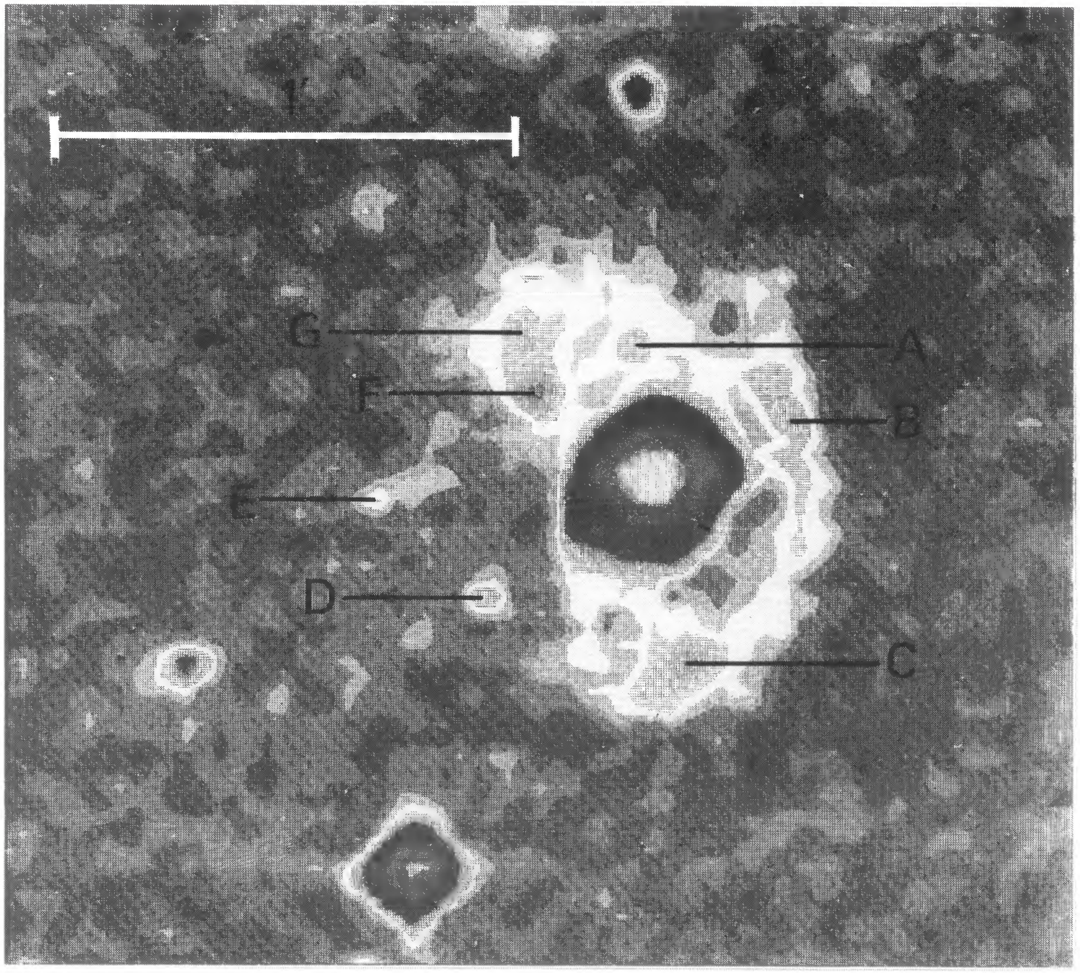

FIG. 1.—Image of the optical counterpart of IRAS 02366−3101. The image has been obtained using the Guide Star Astrometric Package (GASP) of the STScI. North is up, and east to the left. Several knots—in the ring—are visible and have been marked as A–G.

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TABLE 1

PARAMETER CHARACTERISTICS OF THE Hβ AND Hα EMISSION-LINE COMPONENTS[a]

Line	Flux (10^{-14} ergs cm^{-2} s^{-1})	Peak Intensity (10^{-15} ergs cm^{-2} s^{-1} Å^{-1})	Velocity (km s^{-1})	$V - V_{\rm system}$[b] (km s^{-1})	FWHM (km s^{-1})
Hβ narrow	1.50	...	18,152	...	657
Hβ blue broad	5.00	0.49	16,031	−2150	3010
Hβ red broad	3.60	0.41	21,095	+2914	2920
Hα narrow	6.95	...	18,209	...	485
Hα blue broad	9.80	1.2	16,092	−2089	2578
Hα red broad	7.80	0.9	21,088	+2920	2307
[N II] λ6584	4.30	...	18,181	...	490
[O III] λ5007	2.20	...	17,760	−421	800

[a] Velocities have been obtained using the expression $1 + z = [(c + V)/(c - V)]^{0.5}$.

[b] We assume as system velocity the mean value of the Hβ and Hα narrow components, i.e., $V_{\rm system} = 18{,}181$ km s^{-1}.

TABLE 2

FAR-INFRARED PROPERTIES OF IRAS 02366−3101 AND ACCRETION DISK CANDIDATES

Galaxy Name	Redshift	$f_\nu(12)$ (Jy)	$f_\nu(25)$ (Jy)	$f_\nu(60)$ (Jy)	$f_\nu(100)$ (Jy)	log $L_{\rm FIR}$ ($L_\odot$)	α(60, 25)	α(100, 60)
IRAS 02366−3101	0.0629	0.25	0.28	0.75	1.53	10.94	−1.13	−1.40
Mrk 668	0.0767	<0.40	0.38	0.74	<1.00	<10.43	−0.76	−0.59
3C 390.3	0.0570	<0.25	0.29	<0.40	<1.00	<10.02	−0.37	−1.79
Arp 102B	0.0244	<0.14	0.28	0.29	<0.72	<9.14	−0.04	−1.78
Seyfert 1	...	...	...	...	...	...	−1.0	−1.1
Seyfert 2	...	...	...	...	...	...	−1.2	−0.8
H II	...	...	...	...	...	...	−1.8	−0.6

the flux of the blue component is 1.3 times that of the red component.

A similar procedure was used to fit the Hβ emission-line profile. The parameters corresponding to the best fit are also presented in Table 1. While the velocity shifts agree with those obtained for the Hα components, the two broad Hβ components (with FWHM $\approx$ 2965 km s^{-1}) are broader than the corresponding Hα (with FWHM $\approx$ 2440 km s^{-1}).

It is also possible to derive the Hα/Hβ ratio for the narrow and the two broad components. However, deconvolution techniques of blended lines produce uncertainties in the flux distribution for each component. In this particular case, repeated measurements give the same line flux with 20% of uncertainty for each component. Moreover the line flux has a strong dependence on the continuum level, and since the spectral energy distribution of IRAS 02366−3101 is not flat, particularly in the Hβ region (see Fig. 1), large uncertainties occur when placing the continuum level. These two effects preclude the use of the Hα/Hβ ratio to estimate very precisely the amount of extinction present in the different components. This interesting measurement must await higher spectral resolution data with better signal-to-noise ratio.

4. DISCUSSION

4.1. *Accretion Disk Models*

A number of recent detailed models (Dumont & Collin-Souffrin 1990; Chen & Halpern 1989) explain the double-peaked broad profile observed in the Balmer emission lines of some active galaxies (3C 390.3: Pérez et al. 1988; Arp 102B: Chen et al. 1989; 3C 332: Halpern 1990) as emission generated in an accretion disk around a supermassive black hole.

The models of Dumont & Collin-Souffrin (1990) consider that most of the low-ionization broad emission lines come from the outer regions of a thin Keplerian accretion disk which is illuminated by a backscattered ionizing radiation. These models predict that double-peaked broad emission-line profiles can be obtained only if the outer radius has a size of 1000 in units of GM/c^2. They also predict that the Hβ line should be broader than the Hα line as it is measured in the spectrum (see Table 1). However, although the Dumont & Collin-Souffrin models could reproduce the double peak and the FWHM of the lines, the emission peaks appear symmetrically distributed with respect to the system velocity, i.e., to the hydrogen Balmer narrow components, contrary to what is detected in IRAS 02366−3101. The lack of agreement between these models and our observations can be solved if relativistic effects are taken into account.

Relativistic accretion disk models like those of Chen & Halpern (1989) make two strong predictions concerning the emission-line profile, independently of how broad the line is and how separated the two components are. These predictions are first, the blue component will always have a peak intensity larger than the red component due to relativistic boosting effects, and second, the red component will always have a larger velocity difference with respect to system, due to gravitational redshift. These two predictions are confirmed in the observed Hα and Hβ broad profiles of IRAS 02366−3101 (see Table 1). Furthermore, the double-peaked broad emission-line profile of IRAS 02366−3101 (see Fig. 3) is similar to the one obtained by Chen & Halpern (1989) for a small accretion disk, with the size of the inner and outer radius corresponding to 350 and 1000 in units of GM/c^2, respectively, and an inclination of the disk axis of around 15° with respect to our line of sight.

Our detection of the double-peaked broad Hβ and Hα emission-line profiles and the match to theoretical models therefore indicates that a likely scenario for the quasar-type activity detected in IRAS 02366−3101 is emission from an accretion disk around a massive black hole. The presence of a black hole has also been suggested very recently in other luminous *IRAS* galaxies like NGC 6240 (Bland-Hawthorn, Wilson, & Tully 1991) and the Superantennae (Colina, Lipari, & Mac-

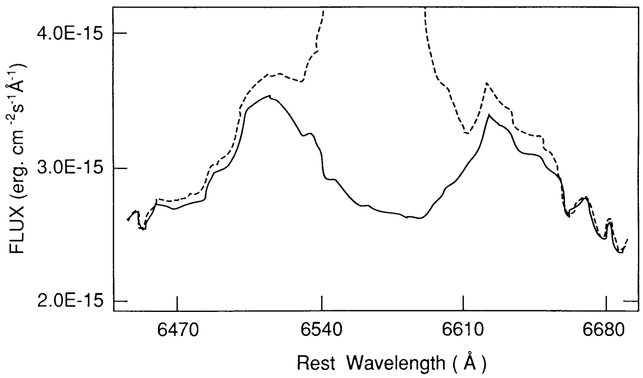

FIG. 3.—Double-peaked broad Hα emission line profile showing the two broad components after subtraction of the Hα and [N II] narrow emission lines. The results of the fit are listed in Table 1.

chetto 1991) based on kinematic and energetic considerations, respectively.

4.2. *Alternative Models*

Although these single-epoch double-peaked emission-line profiles in IRAS 02366−3101 are well fitted by relativistic accretion disk models, these are not the only physical models capable of generating such profiles. It is also not clear if the accretion disk scenario is valid to explain the broad emission line profile of AGNs in general and if it can be maintained when the response of the emission-line region to a variable continuum source is considered.

Sulentic and collaborators (Sulentic et al. 1990) compared the predictions of the disk models and a large sample of broad emission-line profile parameters and concluded that the disk must be almost completely obscured in most AGNs or otherwise not to be a significant source of low-ionization line radiation. Time-variable double-peaked broad emission-line profiles have been obtained in galaxies like Arp 102B (Miller & Peterson 1990), 3C 390.3 (Veilleux & Zheng 1991), and OX 169 (Stockton & Farnham 1991). These observations show that the axisymmetric accretion disk scenario alone cannot fit completely the observed profiles. In fact, Veilleux & Zheng (1991) consider that models involving inhomogeneous disk or biconical BLR are the more successful in explaining the 3C 390.3 profiles while Stockton & Farnham (1991) suggest both a bipolar geometry or a binary supermassive black hole system for OX 169. Finally, Miller & Peterson (1990) show that, at least at some epochs, the broad emission-line profile in Arp 102B cannot be explained in terms of an axisymmetric relativistic accretion disk alone, and a second different broad emission line component should be included.

Models invoking a spherical distribution of gas clouds with radial motions (Robinson et al. 1990) could generate a large variety of line profiles and, among them, double-peaked profiles. If a variable continuum source is considered and the response of the emitting-line regions is computed, profile characteristics similar to those observed in IRAS 02366−3101, i.e., the blueward peak more intense than the redward peak, and maybe even the different velocity shifts of the two broad components, could be generated (E. Pérez, private communication). However, there is increasing evidence that the radiation field in AGNs is anisotropic (see, i.e., Colina et al. 1991a and references therein). If so, the convolution of the gas cloud distribution with the radiation field would have a more planar geometry that should be taken into account.

Models considering different geometries and kinematical behaviors make definite predictions about how the overall broad emission-line profile will change as a function of continuum variability. Therefore, periodic observations over a long period of time of some of the accretion disk candidate galaxies together with detailed models involving continuum variability effects and different geometrical and kinematical BLR configurations (Robinson et al. 1990; Welsh & Horne 1991) are needed before a firm conclusion about the validity of the different models is reached.

Finally, one should note that additional complications, like those generated by differential extinction effects that could strongly modify the line profile, have not yet been implemented in any of the previous models.

4.3. *Comparison with Other Accretion Disk Candidates*

The far-infrared characteristics of IRAS 02366−3101 are compared in Table 2 with those of some other accretion disk candidates like Mrk 668 (Osterbrock & Cohen 1979), 3C 390.3 (Pérez et al. 1988), Arp 102B (Chen et al. 1989) for which *IRAS* measurements are available. Also, the far-infrared spectral distribution of H II, Seyfert 2, and Seyfert 1 galaxies (Miley et al. 1985) are listed in the same table.

It is clear that the accretion disk candidates do not have any common property in their far-infrared characteristics. They cover a range of almost two orders of magnitude in FIR luminosity while the spectral energy distribution is very different from galaxy to galaxy. The luminous *IRAS*-selected IRAS 02366−3101 has a spectral index similar to that of *IRAS*-selected Seyfert 1 galaxies, while the compact blue selected Mrk 668 (which is also the radio source OQ 208) has the flatter spectral energy distribution of all the four candidates. On the other hand, 3C 390.3 (luminous broad-line radio galaxy) and Arp 102B (low-luminosity active galaxy) have a very similar energy distribution with a flat component at large frequencies (25 μm) and a very steep component at low frequencies.

If the same physical scenario is valid for all these disk candidates, their far-infrared energy distribution indicate a different combination of nonthermal emission from the accretion disk and thermal emission from dust reradiation.

4. SUMMARY

We have reported the detection of double-peaked broad Hα and Hβ emission-line profiles in the spectrum of the *IRAS* luminous galaxy IRAS 02366−3101 ($\log L_{\rm FIR} = 10.94\ L_\odot$).

The broad emission-line profiles consist of two components with mean velocity shifts $V_{\rm blue} - V_{\rm sys} = -2120$ km s^{-1} and $V_{\rm red} - V_{\rm sys} = +2911$ km s^{-1}, respectively, while the flux of the blue component is around 1.2 times that of the red component. Also the Hβ broad emission-line components are broader than the corresponding Hα components with FWHM(Hβ) − FWHM(Hα) $\approx$ 525 km s^{-1}.

These observed single-epoch broad Balmer emission-line profiles of IRAS 02366−3101 are consistent with models of inclined small relativistic accretion disks around a massive black hole like those of Chen & Halpern (1989). Therefore, IRAS 02366−3101 is a strong candidate to harbor an accretion disk in its nucleus.

However, periodic observations over a long period of time are needed in order to detect any change in the broad emission-line profile and therefore to check the consistency of the profile with accretion disk models or with other alternative models like those considering radial flows and variability effects.

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