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THE DETECTION OF WOLF-RAYET STARS IN A VERY POWERFUL FAR-INFRARED GALAXY: DIRECT EVIDENCE FOR A STARBURST

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ABSTRACT

Spectra covering the wavelength range 4476–7610 Å are presented for the powerful far-infrared galaxy IRAS 01003−2238. We interpret the broad emission band centered at a rest wavelength of $\lambda \approx 4660$ Å, and other broad weaker features, as arising from the combined effect of approximately 10^5 late Wolf-Rayet stars of the WN subtype. This represents perhaps the most direct evidence to date for the presence of a large number of hot massive stars in the nucleus of a very powerful far-infrared galaxy ($L_{FIR} \approx 7 \times 10^{11}\ L_{\odot}$, $L_{FIR}/L_B \approx 67$). The high number of Wolf-Rayet stars in relation to the number of O-type stars (inferred from the flux ratio of the 4660 Å and Hβ features) may be interpreted as arguing against continuous steady state star formation in 01003−2238, in favor of a recent burst of star formation occurring approximately 10^7 yr ago.

Subject headings: galaxies: general — stars: massive — stars: Wolf-Rayet

I. INTRODUCTION

To better understand the process of energy production in extremely powerful ($L_{FIR} \approx 10^{11}$–$10^{12}\ L_{\odot}$) far-infrared galaxies, we have undertaken an optical long slit spectroscopic survey of a group of galaxies chosen to have far-infrared spectral energy distributions similar to the prototypical class members Arp 220, NGC 6240, NGC 3690, and Mrk 231. A detailed description of the selection process can be found in Heckman, Armus, and Miley (1987, hereafter HAM 1987). The galaxy designated as IRAS 01003−2238 at $z = 0.1176$ is a member of this group having $L_{FIR} \approx 7 \times 10^{11}\ L_{\odot}$ and $L_{FIR}/L_B \approx 67$ (we take $q_0 = 0$ and $H_0 = 75$ km s^{-1} Mpc^{-1}).

The most striking feature in the spectrum of 01003−2238 is the presence of a broad emission band at a rest wavelength of $\lambda \approx 4660$ Å. We interpret this band as arising from the contribution in the integrated spectra of about 10^5 Wolf-Rayet stars. If correct, our results furnish strong constraints for existing theories concerning the nature of the power sources in highly luminous infrared galaxies.

II. OBSERVATIONS AND DATA REDUCTION

The relevant instrumental parameters of our observations are listed in Table 1 (see also HAM 1987). In all cases the data have been flat-fielded, have had a dispersion solution applied, and have been sky-subtracted using the standard procedure in the NOAO "Longslit" package in IRAF.

The 1985 December spectrum was not obtained under photometric conditions. The relative intensities as a function of wavelength have, however, been established using observations of standard stars. The 1987 January spectrum has not been calibrated in terms of either absolute or relative fluxes. Our only measure of the absolute fluxes comes from the imaging data discussed in HAM (1987) and Armus, Heckman, and Miley (1987). These data were then used to place the spectra on an absolute flux scale.

III. RESULTS

The two spectra of 01003−2238 are displayed in Figures 1*a* and 1*b*. From the wavelengths of the narrow components of the forbidden and Balmer lines (see below) we derive a heliocentric redshift of $z = 0.1176$ (supplanting the value of $z = 0.118$ quoted in HAM).

Figure 1*a* shows the broad emission feature extending from 5175 Å to 5235 Å (4633–4687 Å in the galaxy rest frame). This "band" clearly has two peaks with a questionable third peak at the center. The leftmost peak is identified with the He II λ4686 line prominent in the spectra of Wolf-Rayet stars. The low-wavelength peak is most easily identified with the N III blended multiplet λλ4634, 4640, 4642. The region emitting these lines is unresolved spatially in our spectra (< 1″.5 or < 3 kpc in size). Figure 1*a* also shows that the forbidden and Balmer lines are extremely wide ($\Delta v \approx 10^3$ km s^{-1} for Hβ) and show pronounced blue wings. This result, which has significance in the light of theories concerning winds from powerful far-infrared galaxies (HAM 1987), will be discussed in detail in a future paper.

A low-dispersion spectrum of 01003−2238 is shown in Figure 1*b*. Notice the weak emission between 6365 Å and 6560 Å. The broad bump just blueward of 6500 Å is tentatively identified with the C III λ5696, and N IV λ5737 lines, both appearing in the spectra of late Wolf-Rayet stars (Torres and Massey 1987). We identify the strong feature at 6559 Å as that of He I λ5876 which is listed in tables of near-infrared lines of WN stars by Vreux, Dennefeld, and Andrillat (1983). Finally, there is a relatively broad band between 7875 Å and 7965 Å. This broad feature is probably a mixture of the following lines seen in the spectra of Wolf-Rayet stars (Vreux, Dennefeld, and Andrillat 1983); a C II λλ7046, 7053, 7064 triplet, C IV λ7061, He I λ7065, a C II multiplet between 7112 Å and 7144 Å, and an N IV group between 7103 Å and 7129 Å.

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TABLE 1

OBSERVATIONS[a]

Date	P.A.	Slit	Pixel Size	Spectral Range (Å)
1985 Dec	90°	1″.5	0″.73 × 5.7 Å	5495–8775
1987 Jan	110	2.0	0″.73 × 1.6 Å	5000–5900

[a] Both observations made with the CTIO 4 m telescope equipped with the Ritchey-Chrétien spectrograph with the GEC CCD.

The spectral properties of 01003−2238 discernible from these observations are presented in Table 2 (including equivalent widths, observed fluxes, and the reddening corrected luminosities of Hβ, and the emission blend at a rest wavelength of ∼4660 Å).

Reddening corrections were derived from the observed Hα/Hβ ratio assuming an intrinsic ratio of 2.85 and a standard interstellar reddening curve (Osterbrock 1974). These corrections are likely to be underestimates, since in a situation in which the dust and ionized gas are mixed together, the true extinction can be much larger than that implied by the Balmer decrement. Moreover, it may not be appropriate to use a standard reddening curve for these powerful far-infrared galaxies in general.

IV. INTERPRETATION

The simplest interpretation of the broad emission feature near a rest wavelength of 4660 Å seen in 01003−2238, is that this galaxy contains a large number of Wolf-Rayet stars in its nucleus. Since Wolf-Rayet stars are generally believed to be the descendants of O stars with initial masses $M \geq 20$–$40\ M_\odot$ (Abbott and Conti 1987; Chiosi 1982), their presence in 01003−2238 represents strong evidence for a large population of hot, massive (young) stars. Further, an estimate of the number of Wolf-Rayet stars and massive O stars can provide clues to the star formation history of 01003−2238.

As a first step in determining the population of Wolf-Rayet stars in 01003−2238, we have attempted to choose the class of Wolf-Rayet star that best reproduces the emission seen in Figure 1. The approximately equal strengths of the N III λλ4634, 4640, 4642 group of lines, and the He II λ4686 line in the spectrum of 01003−2238 is indicative of the presence of late WN stars (Smith and Kuhi 1981). Also, the great strength of the N III lines, relative to those of the N V λλ4604, 4620 lines (actually not visible in 01003−2238) is consistent with this conclusion. In 01003−2238 the contribution of the C III λλ4647, 4650, 4652 lines might just be visible as a broadening of the N III peak to longer wavelengths. Comparing Figure 1*a* then, with the Wolf-Rayet spectra collected by Smith and Kuhi (1981), we have arrived at the WN8 subtype as representative of the WN stars present in 01003−2238.

It is most natural to assume a mixture of WN and WC types in the spectrum of a galaxy suspected of producing a large number of massive stars. We feel that there is no strong evidence for the presence of WC stars in the spectrum of 01003−2238, in part due to the absence of lines such as C IV λ4658 and C IV λλ5801, 5812, which are present in the spectra of WC stars (Torres and Massey 1987). In the calculations that follow, we take a WN8 subtype as the representative Wolf-Rayet star found in the nucleus of this galaxy.

The flux in the emission band between 5175 Å and 5235 Å (hereafter the 4660 Å band) from Table 2 is $F_{\lambda 4660} = 8.45 \times 10^{-16}$ ergs cm^{-2} s^{-1}. This implies an extinction-corrected luminosity of $L_{\lambda 4660} \approx 2.9 \times 10^{41}$ ergs s^{-1}. As can be seen in Table 3, 01003−2238 rivals Mrk 309 (Osterbrock and Cohen 1982) as the most luminous "Wolf-Rayet galaxy" known (both are 10–1000 times more luminous than the other 11 galaxies listed). To estimate the number of Wolf-Rayet stars in 01003−2238 we have followed the methods of both Osterbrock and Cohen (1982) and Kunth and Sargent (1981), which we now discuss in turn.

The flux density in the continuum near the 4660 Å feature is $S_\lambda = 5.63 \times 10^{-17}$ ergs cm^{-2} s^{-1} Å^{-1}. This translates, after application of the reddening correction described in the previous section, to a power of $P_{\lambda 4660} = 2.16 \times 10^{40}$ ergs s^{-1} Å^{-1}, corresponding to an absolute magnitude of $M = -21.19$ near 4660 Å in the rest frame of 01003−2238 (Oke and Schild 1970). Smith and Kuhi (1981) give 50 Å as the typical equivalent width of a Galactic WN8 star. For 01003−2238 we have measured the equivalent width as 15 Å, which implies that approximately 30% of the continuum near the 4660 Å band is contributed by WN8 stars. Using $M_{\lambda 4660} = -7.1$ as the value for a single WN8 star (van der Hucht *et al.* 1979; van der

TABLE 2

IRAS 01003−2238

Parameter	Value
z	0.1176
$F_{H\alpha}$ (ergs cm^{-2} s^{-1})	8.50×10^{-15}
$F_{\lambda 5007}$ (ergs cm^{-2} s^{-1})	6.97×10^{-15}
$F_{H\beta}$ (ergs cm^{-2} s^{-1})	1.38×10^{-15}
$F_{\lambda 4660}$ (ergs cm^{-2} s^{-1})	8.45×10^{-16}
$EQW_{H\beta}$ (Å)	24.5
$EQW_{\lambda 4660}$ (Å)	15.0
$L_{H\beta}$ (ergs s^{-1})[a]	4.53×10^{41}
$L_{\lambda 4660}$ (ergs s^{-1})[a]	2.90×10^{41}
$L_{\lambda 4660}/L_{H\beta}$	0.64

[a] Corrected for extinction (see text). We take $H_0 = 75$ and $q_0 = 0$.

TABLE 3

WOLF-RAYET GALAXIES

Object	$F_{WR}/F_{H\beta}$[a]	L_{WR} (ergs s^{-1})[b]	L_{FIR} (ergs s^{-1})[c]
01003−2238	0.61	2.9×10^{41}	2.8×10^{45}
Mrk 309	0.67	4.5×10^{41}[d]	6.1×10^{44}
NGC 6764	0.43	2.1×10^{40}[d]	4.4×10^{43}
HE 2-10	0.13	1.7×10^{40}[d]	1.8×10^{43}
Tololo 3	0.09	1.3×10^{38}[d]	3.9×10^{42}
Mrk 750	0.08	6.4×10^{38}[d]	1.4×10^{41}
Tololo 89	0.09	4.4×10^{38}[d]	2.5×10^{42}
II Zw 40	0.02	uncalibrated	2.4×10^{42}
NGC 5430	0.57	2.6×10^{40}[e]	1.2×10^{44}
Mrk 710	0.26	7.2×10^{39}[f]	6.1×10^{42}
Mrk 724	0.04	9.0×10^{37}[f]	undetected
Mrk 1089	0.20	2.6×10^{40}[f]	7.1×10^{43}
Mrk 1236	0.06	7.4×10^{38}[f]	1.0×10^{43}

[a] The ratio of the flux in the 4660 Å (or 4650 Å) band to the flux in the Hβ line (uncorrected for reddening).

[b] The luminosity in the 4660 Å (or 4650 Å) band, corrected for reddening.

[c] L_{FIR} is the far-infrared luminosity constructed using the far-infrared flux as defined in *Catalogued Galaxies and Quasars Observed in the IRAS survey* (Lonsdale *et al.* 1985). Mrk 309 and Mrk 750 were detected at 25 μm and 60 μm but not at 100 μm. The quoted L_{FIR} is νP_ν at 60 μm.

[d] Luminosity taken directly from Kunth and Joubert 1985.

[e] Luminosity taken from Keel 1982.

[f] Luminosity taken from Kunth and Schild 1986.

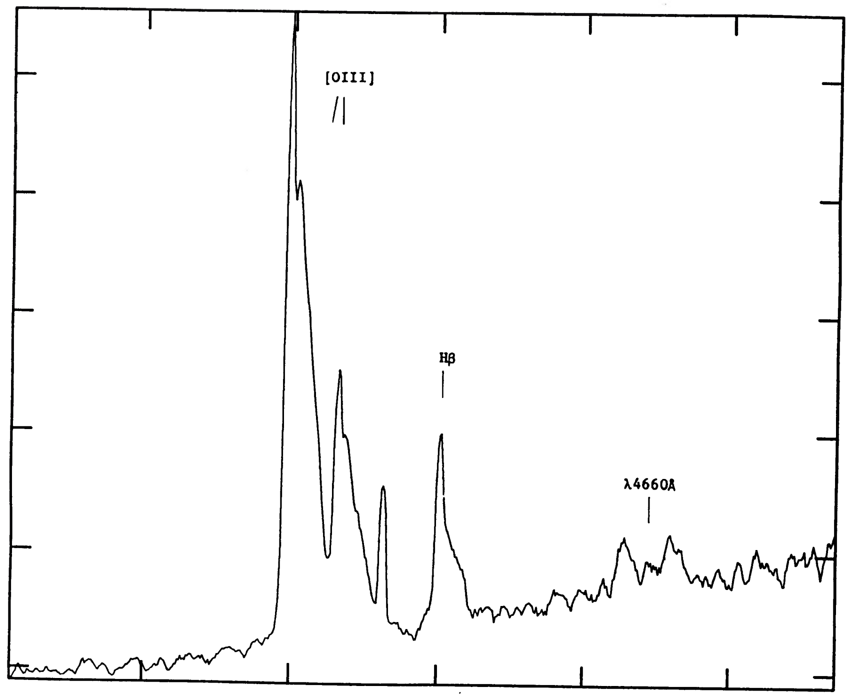

FIG. 1a

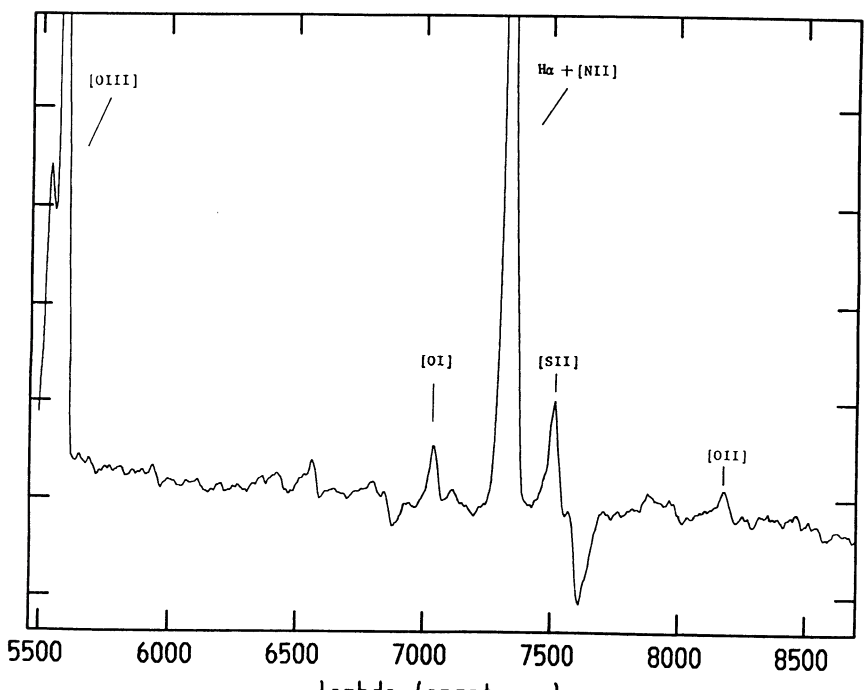

FIG. 1b

FIG. 1.—(*a*) High-dispersion, smoothed spectrum of the nucleus of IRAS 01003 − 2238, spanning a range in wavelength of 5000–5900 Å, taken at a P.A. = 110°. Marked are the lines of [O III] λλ4959, 5007, Hβ, and the broad Wolf-Rayet feature at a rest wavelength of 4660 Å. The feature between the [O III] lines and Hβ is due to the impingement of a cosmic ray on the detector. The *y*-axis is in arbitrary intensity units. (*b*) Low-dispersion, smoothed spectrum of the nucleus of IRAS 01003 − 2238, taken at a P.A. = 90°. Marked are the lines of [O III] λλ4959, 5007, [O I] λ6300, [N II] λλ6548, 6584, Hα, [S II] λλ6717, 6731, and [O II] λ7320. The [O III] lines and the Hα line have been clipped in order to bring out the weaker features. The *y*-axis is in arbitrary intensity units.

Hucht and Conti 1981), we arrive at a total of approximately 130,000 WN8 stars in 01003−2238. The Hβ luminosity can be used to determine the number of O stars of a given type in 01003−2238 (Osterbrock 1974), assuming the emitting region is optically thick to Lyman-continuum photons. Using tables in Osterbrock (1974) for $T = 10^4$ K and $N_e = 10^4$ cm^{-3}, and the reddening corrected Hβ luminosity given in Table 2, we calculate that 9.5×10^{53} s^{-1} ionizing photons are required, which corresponds to either 2.0×10^4 O5 stars, 1.4×10^5 O7 stars, or 5.4×10^5 O9 stars. Taking the O7 stars as representative, following Osterbrock and Cohen (1982), we get a ratio of Wolf-Rayet to O7 stars of WR/O ≈ 0.94 in 01003−2238.

Alternatively, we can use the value for the 4660 Å luminosity of a typical Wolf-Rayet star implied by the calculation of Kunth and Sargent (1981). We then arrive at approximately 3.1×10^5 WN stars. Similarly, using the same initial mass function as Kunth and Sargent (1981), along with our reddening-corrected Hβ luminosity, we calculate that 5.8×10^5 OB stars with $M \geq 8\ M_\odot$ or 1.1×10^5 O4–O9 stars are required in 01003−2238. Using these population estimates, we have a Wolf-Rayet to OB star ratio of WR/OB ≈ 0.53, and a Wolf-Rayet to O4–O9 star ratio of WR/O4–O9 ≈ 2.8.

Thus, using either the estimating procedures of Osterbrock and Cohen or Kunth and Sargent, the WR to O star ratio in 01003−2238 is between 10 and 70 times that estimated for the Milky Way (Conti 1982; Firmani 1982). Our calculations assume that only O stars contribute to the ionization equilibrium in the emitting region. In fact the line ratios in 01003−2238 do not resemble those of ordinary H II regions, strongly suggesting that much of the emission-line gas is excited by a more "exotic" source than OB stars (possibly an AGN and/or shocks driven by a "superwind," as discussed in HAM 1987). Thus the ratios of Wolf-Rayet to O stars are probably only lower limits to the actual values.

A model-independent, but useful, procedure is to divide the flux in the 4660 Å band by the Hβ line flux for 01003−2238 and to compare this ratio to those given for the other galaxies with Wolf-Rayet features in their spectra. The values of these ratios are listed in Table 3, where it can be seen that 01003−2238 occupies the high end of the 4660 Å to Hβ ratio range, indicating that it has an unusually large relative number of Wolf-Rayet stars, even in comparison to the other "Wolf-Rayet" galaxies in the literature.

If star formation in a galaxy occurs continuously at a roughly steady rate, then we would expect the number ratio of Wolf-Rayet to massive O stars to be equal to the ratio of the time spent in each stage. Taking an O star main-sequence lifetime of 6×10^6 yr, approximately 5% of this, or 3×10^5 yr, will be spent in the He-burning post–main-sequence stage, in rough agreement with the relative numbers of Wolf-Rayet and O stars in the Milky Way (Firmani 1982). In contrast, the Wolf-Rayet to O star ratio in 01003−2238 is more than an order of magnitude larger than this. As Kunth and Sargent (1981) have argued for Tololo 3, we believe that the high relative number of Wolf-Rayet stars with respect to O stars in 01003−2238 argues against a continuous star-formation rate. Instead, if the rate of star formation has declined strongly in this galaxy during the last 10^7 yr, many of the most massive stars would have had time to evolve off the main sequence into a Wolf-Rayet or supergiant phase. The idea that exponentially declining star formation rates best fit the observed properties of some powerful far-infrared galaxies is not new, and it has been explored and modeled in detail for M82 (Rieke *et al.* 1980), Arp 220 and NGC 6240 (Rieke *et al.* 1985), and NGC 3690 (Gehrz, Sramek, and Weedman 1983).

Alternatively, the strength of the 4660 Å feature relative to Hβ in 01003−2238 may arise from a highly nonstandard IMF at the high-mass end (i.e., one producing more Wolf-Rayet stars per unit Lyman-continuum luminosity). It is also possible that the relative number of Wolf-Rayet and O stars produced by a steady rate of star formation may be a strong function of metal abundance (cf. Maeder, Lequex, and Azzopardi 1980). Finally, we cannot entirely exclude the possibility that the Wolf-Rayet features are due to exotic objects like supermassive Wolf-Rayet stars (Cassinelli, Mathis, and Savage 1981), or even a peculiar AGN. Nevertheless, the most natural explanation of the Wolf-Rayet features in 01003−2238 is that the star-formation rate has declined steeply over the last 10^7 yr in this galaxy.

V. CONCLUSIONS

We have analyzed the optical spectrum of the very powerful far-infrared galaxy IRAS 01003−2238 ($L_{\rm FIR} \approx 10^{12}\ L_\odot$) which shows a broad emission feature centered on the rest wavelength of 4660 Å. This feature is interpreted as arising from the combined effect of approximately 10^5 Wolf-Rayet stars of the WN8 subtype. Other broad (but weaker) spectral features are consistent with this interpretation. Compared to other galaxies whose spectra exhibit Wolf-Rayet lines, the estimated number of Wolf-Rayet stars, the ratio of the 4660 Å to Hβ flux, and the number of Wolf-Rayet stars with respect to massive O stars in 01003−2238 are unusually large.

These results have two highly significant implications for our understanding of very powerful ($L_{\rm FIR} \approx 10^{12}\ L_\odot$) far-infrared galaxies like 01003−2238. First, the detection of Wolf-Rayet stars represents perhaps the best evidence to date for a large population of hot, massive, young stars in such galaxies. Unfortunately, uncertainties concerning the proper extinction correction to use preclude the possibility of quantitatively evaluating the fraction of $L_{\rm FIR}$ that might be powered by young stars. Second, the fact that the ratio of Wolf-Rayet to O stars is probably enhanced by at least one to two orders of magnitude over that in the Milky Way is most naturally interpreted as evidence that the star-formation rate has declined sharply over the last 10^7 yr in 01003−2238. Together the above results provide strong support for the interpretation of very powerful far-infrared galaxies as objects that have recently undergone an epoch (of short duration) characterized by a very high star-formation rate (a "starburst").

Since 01003−2238 is a member of a class of powerful far-infrared galaxies selected on the basis of IR spectral distribution, we might expect the 4660 Å feature to be visible in other galaxies in our sample. To date, having studied several dozen galaxies in our sample, we have found no convincing evidence for the presence of Wolf-Rayet stars in the nuclei of these galaxies. Of relevance to the search is the fact that 01003−2238 has the bluest broad-band color ($B-R = 0.59$) of all the galaxies measured (Armus, Heckman, and Miley 1987). This might be indicating that either less overall obscuration, or a more favorable viewing angle, is permitting an unusually clear look at the region of the starburst. Higher signal-to-noise ratio spectra of other blue galaxies in our infrared sample might provide more evidence linking starbursts to powerful far-infrared emission.

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