1991ApJ...378..302C

THE ASTROPHYSICAL JOURNAL, 378:302–306, 1991 September 1

IRAS 17380−3031: A NEW DUSTY LATE WC-TYPE WOLF-RAYET STAR

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Received 1990 November 15; accepted 1991 March 13

ABSTRACT

Systematic 12 μm flux-limited surveys of the complete *IRAS* LRS (Low Resolution Spectrometer) data base show that late-type WC (WCL) stars with circumstellar dust emission have unique mid-infrared spectra, suggesting a new method for the detection of such stars. By optical spectroscopy, we have confirmed that the prime LRS-selected WCL candidate, IRAS 17380−3031, is a very red WCL star. We classify it as WC8–9, with a probable distance of 3 ± 1 kpc, and a total extinction of $A_v \sim 12.5$ mag. This confirmation demonstrates the power of the LRS technique for discovery of dusty WCL stars with *IRAS*.

Subject headings: infrared: sources — stars: circumstellar shells — stars: individual (IRAS 17380−3031) — stars: Wolf-Rayet

1. INTRODUCTION: WOLF-RAYETS IN THE INFRARED

The Wolf-Rayet stars (WRs) represent a small population of evolved high-mass stars (Abbott & Conti 1987) whose physical and atmospheric attributes tell us much about high-mass stellar evolution (Maeder 1990; Maeder & Meynet 1987). The WRs are divided into two main sequences: WC and WN. The WC objects have spectra dominated by emission lines of C and He ions. WN spectra are dominated by N ions. These distinctive spectra arise in vastly extended atmospheres created by powerful stellar winds.

WRs of different sequences have distinct infrared counterparts. WNs present infrared spectra typical of free-free emission of thermal gas (Cohen, Barlow, & Kuhi 1975; Hackwell, Gehrz, & Smith 1974). By sharp contrast, emission from hot (700–1400 K) dust grains is found in WCL (late WCs: WC7–10) stars with a frequency that increases with lateness of subtype (Williams, van der Hucht, & Thé 1987, hereafter WHT; Cohen, Barlow, & Kuhi 1975; Gehrz & Hackwell 1974). The WCE (early WCs: WC3–6) stars usually show free-free emission. However, Williams et al. (1990a) have recently reported an episode of dust formation leading to a shell around the WC4 star, LS 3 (= WR19), similar to those observed around WCLs. One might argue that any WC star may be able to make dust if regions of sufficient density arise in its wind (locally sufficient to negate the generally high degree of excitation and/or of radiative heating in the WCEs). WC7s represent a transition between WCE and WCL stars because dust condensation is known to occur episodically in half the stars studied over long periods (HD 193793, WC7+O5, Williams et al. 1990b; HD 192641, WC7+O8, Williams et al. 1985). Dust may form cyclically as a consequence of enhanced densities in the binaries, perhaps driven by shocked colliding winds (Williams et al. 1990b).

A major problem with defining the distribution of the WCL stars optically is that dust often obscures them heavily, rendering their optical counterparts extremely faint but their infrared emission relatively bright. As an indication of this pattern, note that the best-known WCLs discovered in the past 10–15 yr came from infrared sky surveys. The AFGL Sky Survey (Price & Walker 1976) yielded GL 2104 (= WR112), a WC9 (V = 17.7: Cohen & Kuhi 1976), and GL 2179 (= WR118), a WC9 (Allen et al. 1977; $B = 20$, $R = 16$, Joyce et al. 1977). Danks et al. (1983) discovered a new WC8 (= WR48a; $B = 20$) during a 2 μm survey of a dark cloud in Centaurus. While WHT found that ~80% of the WCL stars that show persistent dust emission re-emit less than 10% of their total luminosity in the infrared, the remaining 20% re-emit more than 50%, suggestive of substantial circumstellar optical depths in these cases. In some stars with high total extinction there exist independent estimates for low values of interstellar extinction (e.g., from Na D line absorptions in Ve 2−45: Cohen, Barlow, & Kuhi 1975; see also Danks et al. 1983; Cohen & Vogel 1978; Cohen & Kuhi 1977; Allen et al. 1977). Therefore, one can conclude that some WCLs suffer appreciable *circumstellar* extinction. Consequently, an "all sky" infrared technique for finding new WCLs would present obvious advantages and eliminate one aspect of bias against these stars in conventional surveys.

In this paper we present infrared photometry of IRAS 17380−3031 and of IRAS 18405−0448, two of the proposed candidates for late WC-type stars suggested by Volk & Cohen (1989a) from their survey of *IRAS* LRS spectra. The overall energy distributions of both these *IRAS* sources mimic those of previously known WCL stars. We report optical spectroscopy for IRAS 17380−3031 which show it to be an extremely reddened WC8–9 star. These results vindicate the "LRS technique" for finding new WCLs.

2. THE LRS SEARCH TECHNIQUE

Roche & Aitken (1984) obtained 8–13 μm spectra of six WC8/9 stars. They interpreted breaks in the spectra near 10 μm as interstellar silicate absorption features against the hot dust continua. Van der Hucht et al. (1985) presented the first *IRAS* LRS spectra of WCLs that emphasized these apparent silicate absorptions.

During their extension of the existing *IRAS* LRS Atlas (1986) to a complete sample with $S_\nu(12) \geq 40$ Jy, Volk & Cohen (1989a) published spectra for 356 *IRAS* sources with high-quality 12 μm fluxes. They classified the LRS spectra into eight categories based on spectral appearance. One such category is the "P" class which accommodates objects with emission bands of polycyclic aromatic hydrocarbons (PAHs) at 7.7, 8.7, 11.3, and 12.7 μm. Within class P, Volk and Cohen noted a very distinctive but rare spectral shape shown by two sources discovered by *IRAS* and shared by the WCL stars discovered by the AFGL survey (GL 2104 and 2179). Figure 1 shows LRS spectra of known WCL stars and of the two candidates for dusty WCLs suggested by Volk & Cohen (1989a); all LRS spectra have been "dewarped" (see Volk & Cohen 1989b). The similarity is striking. (Although the variable WR48a was bright enough in 1983 (111 Jy at 12 μm; WHT) for *IRAS* to have taken an adequate LRS spectrum, it lies in a highly confused region, explaining its absence from even the IRAS Point Source Catalog, Version 2, 1988.)

Cohen, Tielens, & Bregman (1989) explained this unique spectral shape by combining airborne 5–8 μm data with LRS spectra for both Ve 2–45 (= WR 104; WC9) and GL 2104. It is the presence of an emission band (of carbon clusters with perhaps hundreds of C atoms) between 7 and 9 μm that contributes to the peculiar, steeper than Rayleigh-Jeans, signature of the LRS spectra, together with weak interstellar silicate absorption at 10 μm due to distance.

3. INFRARED SPECTROPHOMETRY AND PHOTOMETRY

On 1989 March 29 we obtained near-infrared spectroscopy of IRAS 17380−3031 from the AAT with the "FIGS" instrument in the range 2.02–2.13 μm. This region was chosen because one can distinguish WC8–9 stars from the He I 2.058/C IV 2.08 μm triplet ratio when the stellar emission is not masked by dust (Williams & Eenens 1989). However, in IRAS 17380−3031 the 2 μm spectrum is swamped by thermal emission from circumstellar dust, which happens commonly for WC9s. No line appears with peak above 4% of the continuum. A similar spectral scan of IRAS 18405−0448 also failed to detect any emission lines.

We initially located both sources from their nominal *IRAS* coordinates but were able to refine these by peaking at 2 μm, preparatory to taking the infrared spectra. We found (1950) positions of $17^h37^m59^s.9$ $-30°31'00''$ (peaking in a $2''.1$ aperture) and $18^h40^m33^s.1$ $-04°48'24''$ (peaking in a $5''.9$ aperture). The star IRAS 17380−3031 is the western component of a pair of faint stars elongated in p.a. 80°–260°, with separation ∼3″. The star IRAS 18405−0448 is the western of a pair of roughly comparable stellar images, separated by ∼9″ in p.a. 95°–275°. The optical counterparts of both *IRAS* sources are visually very faint and extremely red.

The stars IRAS 17380−3031 and IRAS 18405−0448 were observed photometrically using the 1 m and 2.2 m telescopes of the European Southern Observatory (ESO) at La Silla, Chile. The near-infrared data (*JHKLM*) were taken with the 1 m

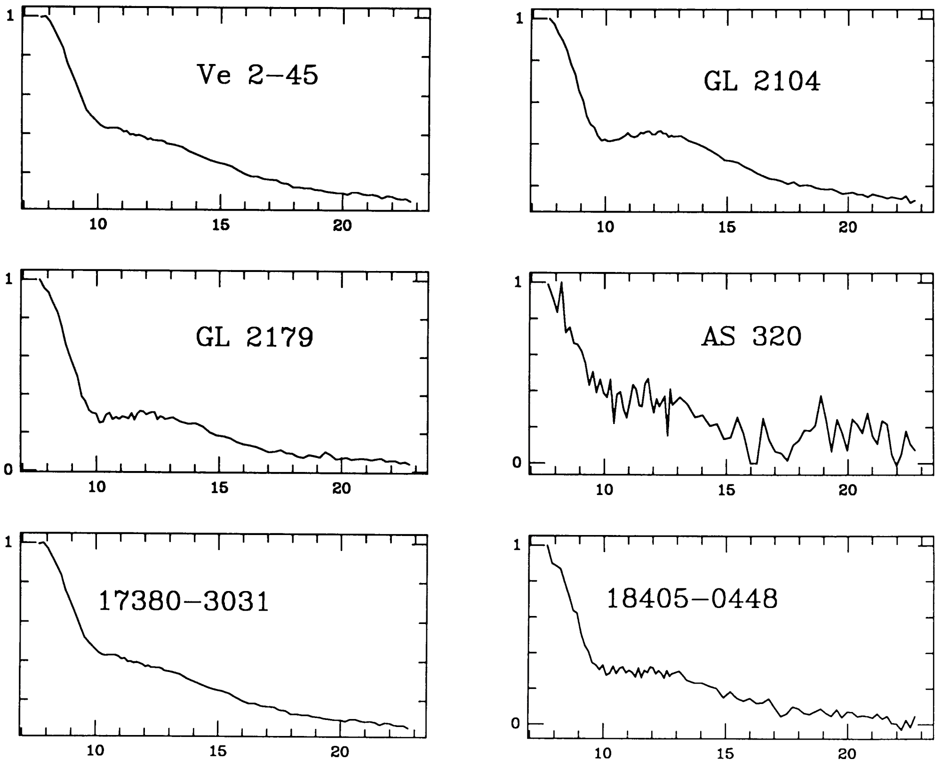

FIG. 1.—Montage of normalized (F_λ) LRS spectra for four already known WCL stars, and two found by the "LRS method": the newly discovered WC8–9 object, IRAS 17380–3031 and the potential new WCL candidate, IRAS 18405−0448. LRS spectra have been overlapped, spliced, and dewarped (see Volk & Cohen 1989b).

TABLE 1

GROUND-BASED INFRARED PHOTOMETRY OF IRAS 17380 − 3031 AND IRAS 18405 − 0448[a]

InSb Observations with the ESO 1 m Telescope

Source (IRAS)	Date	*J* (1.24)[b] (0.32)[c]	*H* (1.63) (0.28)	*K* (2.19) (0.39)	*L* (3.79) (0.68)	*M* (4.64) (0.63)
17380 − 3031..........	1990 March 16	9.64(3)	7.16(1)	4.80(1)	1.64(2)	0.80(2)
17380 − 3031..........	1990 April 10	9.59(4)	7.17(3)	4.83(5)	1.65(2)	0.80(4)
18405 − 0448..........	1989 May 25	10.27(2)	7.33(2)	5.00(3)	2.33(4)	1.62(2)
18405 − 0448..........	1990 April 10	10.21(8)	7.33(2)	4.99(2)	2.36(4)	1.55(5)

Bolometer Observations with the ESO 2.2 m Telescope

Source (IRAS)	Data	*L* (3.76)[b] (0.7)[c]	*M* (4.69) (0.05)	*N*1 (8.38) (0.84)	*N*2 (9.67) (1.65)	*N*3 (12.89) (3.7)	*Q*0 (18.56) (5.6)
17380 − 3031..........	1990 April 5	1.66(4)	0.78(3)	−0.42(9)	−0.06(4)	−0.79(3)	−0.62(14)
18405 − 0448..........	1990 April 6	2.41(3)	1.66(3)	0.47(5)	0.71(6)	−0.31(14)	−0.79(22)

[a] Numbers tabulated represent magnitudes with parenthesized 1 σ errors in 0.01 mag. Nominal central wavelengths and FWHMs are given for all filters.

[b] Numbers in this row are central wavelengths in units of μm.

[c] Numbers in this row are filter FWHMs.

telescope InSb photometer in 1989 May, and in 1990 March and April. The bolometer data (*L*/*M*/*N*1/*N*2/*N*3/*Q*0) were taken with the 2.2 m telescope in 1990 April. The aperture used was always 15″. In each case three or four observations per night were taken, together with standard star observations. The resulting magnitudes as averages per night are listed in Table 1. Standard errors of the mean are given in parentheses (in units of 0.01 mag).

If we compare the spectral energy distributions of IRAS 17380 − 3031 and IRAS 18405 − 0448 with those of the WC9 stars, Ve 2 − 45 and GL 2104, we find that the two new *IRAS* sources are very similar to one another, and both strikingly resemble the previously known WC9s (Fig. 2). The "break" near 10 μm is more obvious in the *IRAS* sources, perhaps because of their greater distance (but note that interstellar silicate absorption contributes only a portion of the apparent dip near 10 μm in Ve 2 − 45: Cohen et al. 1989).

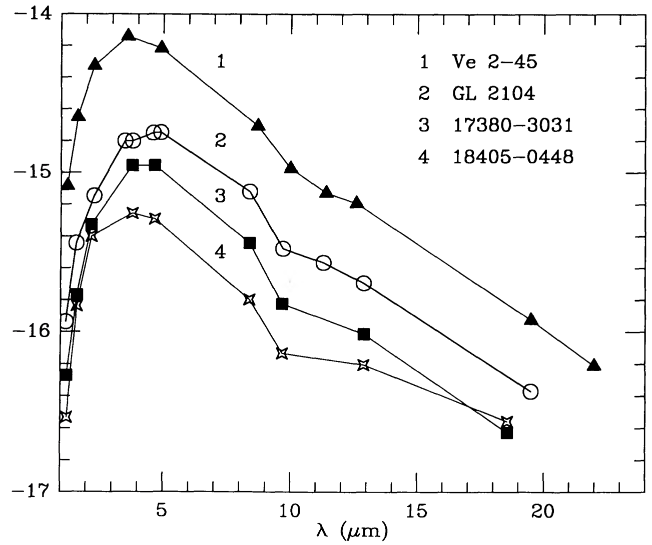

FIG. 2.—Observed spectral energy distributions for the two previously known WC9 stars, Ve 2 − 45 and GL 2104, for the new WCL, IRAS 17380 − 3031, and for IRAS 18405 − 0448, the second WCL candidate suggested by Volk & Cohen (1989a).

4. OPTICAL SPECTROSCOPY OF IRAS 17380 − 3031

On 1990 March 21 we secured a 1000 s exposure of the visual magnitude ~20 optical counterpart to IRAS 17380 − 3031 through a service observation on the 3.9 m Anglo-Australian Telescope. The instrument used was the FORS (Faint Object Red Spectrograph), a low-dispersion collimatorless spectrograph with a GEC CCD chip. The 25 cm camera was used to cover the range λλ5300–10190 (chosen because of the obvious and extreme redness of the optical counterpart) at resolution ~20 Å. A Cu-Ar arc lamp provided the wavelength calibration. The low-metal abundance G0 star HD 126587 was used to remove the atmospheric absorption; at FORS resolution it presents only very weak absorption features. The star HR 5501 provided flux calibration, and an OG 530 filter was used throughout. As an indication of the difficulty required to obtain a conventional classification spectrum of this source, we note that unpublished spectroscopy between 4500 and 7000 Å on the Mt. Stromlo 1.9 m telescope using a blue photon counting array (M. Cohen & R. J. Wainscoat, 1989 May) failed to detect any emission lines after 1200 s of integration.

Figure 3 represents the AAT spectrum that clearly shows an extremely red star with very broad, powerful, emission lines. The star IRAS 17380 − 3031 is indeed a WC star. Table 2 lists the dominant lines that are useful for radial velocity and/or line-width determinations. The table gives observed centroid wavelengths, heliocentric radial velocities, integrated line fluxes, EWs, FWHMs, and identifications of the contributory ions. Parameters were derived from an interactive graphics routine that generates best-fit Gaussian profiles above interpolated continua selected by examination of the local spectrum and provides estimates of 1 σ errors in these parameters based on χ^2 analyses. The tabulated FWHMs represent the intrinsic line widths: observed FWHMs were corrected for an instrumental FWHM of 20 Å on the basis of both ray-traces of the

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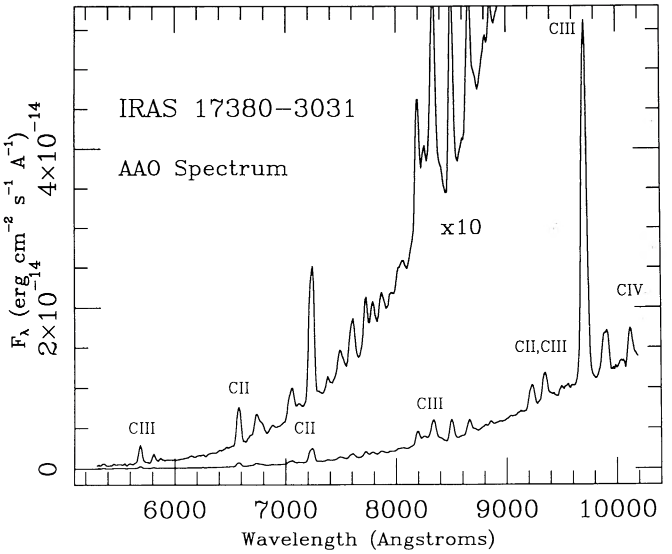

FIG. 3.—Reduced spectrum of the optical counterpart of IRAS 17380−3031 obtained at AAO. The upper spectrum has been scaled up by a factor of 10. Lines are labeled by their dominant ionic contributors.

spectrograph and observations of isolated arc lines with the same slit as used for stellar observations. Line identifications and rest wavelengths were taken from the compilation by Vreux, Dennefeld, & Andrillat (1983). Rest wavelengths for blends represent intensity-weighted wavelengths using the relative line intensities given by Vreux et al. (1983).

We follow Torres, Conti, & Massey (1986, hereafter TCM) for WR classification in the yellow, and Conti, Massey, & Vreux (1990, hereafter CMV) in the near-infrared. The logarithm of [−EW] for the λ5806 C IV doublet is 1.59, suggesting WC9 (TCM, Fig. 2*b*). The logarithmic intensity ratio of C IV/C III λ5696 is −0.40 so IRAS 17380−3031 is WC8–9 from Table 3 of TCM. Note that TCM advocate no longer using the designation of "WC8.5" (see Lundstrom & Stenholm 1984). Turning now to line intensities in the near-infrared, the star is either WC8 or WC9 from the relative strengths of the C II blend λ7232 and the C IV line λ7726. We focus on the following adjacent pairs of lines or blends (to avoid problems with extreme reddening): C IV λ7726 and C II λ7789; C II λ9234 and C III λ9358; and C III λ8664 and C IV λ8856. The star IRAS 17380−3031 definitely possesses attributes of both WC8 and WC9 stars (CMV, Fig. 3*a*). Intrinsic line width is a complementary classification criterion (e.g., TCM). From the means of four unblended C III and three unblended C IV lines we find average FWHMs to be: 1250 ± 50 (C III) and 800 ± 100 km s^{-1} (C IV), consistent with a WC8 to WC9 star (TCM, Fig. 4). We, therefore, classify IRAS 17380−3031 as WC8–9 (shunning type 8.5!).

The average radial velocity of all ionic lines measured is −80 ± 30 km s^{-1} (heliocentric) with no significant distinction between ions (only C III and C IV yielded isolated lines for this determination by ion).

5. DISTANCE AND EXTINCTION

If we form monochromatic, line-free estimates of the continuum levels in IRAS 17380−3031 near V (5556 Å) and R (6700 Å) we find $V-R = 2.78$, with uncertainty ∼0.1. Identically constructed indices for Ve 2−45 ($A_v = 7$, van der Hucht et al. 1988) and GL 2104 ($A_v = 13$, van der Hucht et al. 1988) are 1.62 and 2.85, respectively. Consequently, comparing these color indices with that for IRAS 17380−3031 we estimate that this *IRAS* source suffers approximately the same extinction as GL 2104, and about 5 mag more than that of Ve 2−45 (assuming a normal reddening law between V and R, which is only a coarse approximation in the absence of specific information on the law of circumstellar reddening in these WCL stars). The star IRAS 17380−3031 must, therefore, suffer a total extinction of 12–13 mag. We have examined the optical spectrum for diffuse interstellar bands to provide a check on the extinction, but without obvious success.

With $V \sim 19.7$, $A_v \sim 12.5$, and $M_v \sim -5.0$ (TCM), IRAS 17380−3031 lies ∼3 kpc from the Sun. Estimates of bolometric luminosity for dusty WC8 and WC9 stars are rather uncertain because of the difficulties of determining indepen-

TABLE 2

IDENTIFICATIONS OF DOMINANT LINES IN SPECTRUM OF IRAS 17380−3031

Centroid (Å)	Rest Wavelength (Å)	Radiation Velocity (km s^{-1})	Intensity (ergs cm^{-2} s^{-1})	−E.W. (Å)	FWHM (km s^{-1})	Ion
5689 ± 4	5695.9	−350 ± 200	8.18E−15	120 ± 50	1400 ± 210	C III
5811 ± 3	5806.4	210 ± 170	3.27E−15	40 ± 16	1200 ± 160	C IV
6148 ± 4	6154.0	−310 ± 200	7.98E−16	6 ± 2	1400 ± 280	C II + C III
6578 ± 1	6580.3	−110 ± 40	2.24E−14	70 ± 10	1700 ± 40	C II
7232 ± 1	7234.5	−100 ± 50	1.04E−13	120 ± 15	1900 ± 50	C II
7379 ± 4	7382.	−120 ± 150	4.03E−15	4 ± 2	1200 ± 200	C IV
7602 ± 2	7604.1	−70 ± 90	3.12E−14	20 ± 6	1800 ± 150	C III
7723 ± 3	7726.2	−110 ± 130	1.87E−14	11 ± 4	1000 ± 150	C IV
7789 ± 2	7789.3	−20 ± 60	9.64E−15	5 ± 2	1100 ± 160	C III
8193 ± 1	8196.5	−140 ± 20	5.13E−14	15 ± 2	1300 ± 30	C III
8337 ± 3	8340.0	−90 ± 120	1.13E−13	30 ± 8	1500 ± 140	C III
8501 ± 1	8500.3	10 ± 35	1.30E−13	35 ± 6	1200 ± 50	C III
8658 ± 3	8664.3	−200 ± 130	6.56E−14	15 ± 5	1200 ± 170	C III/He II
8855 ± 5	8856.	−30 ± 180	1.05E−14	2 ± 1	800 ± 220	C IV
9229 ± 1	9234.1	−170 ± 30	1.73E−13	20 ± 3	1450 ± 50	C II
9347 ± 1	9358.4	−350 ± 50	1.84E−13	20 ± 3	1200 ± 50	C III
9710 ± 3	9711.1	−45 ± 100	2.64E−12	240 ± 60	1500 ± 90	C III
10121 ± 5	10121.	10 ± 160	2.48E−13	20 ± 6	1300 ± 260	C IV/He II

dent distances. However, if we assign to IRAS 17380−3031 20000 $L_\odot$, the average of the luminosities for Ve 2−45 and GL 2104, we deduce 3 kpc for this star, with probable uncertainty of ±1 kpc. Its Galactic coordinates ($l = 358°$, $b = 0°$) locate it in the zone of the inner Galaxy where all other WC9s are known to occur. The interstellar extinction in this direction is very patchy (Neckel & Klare 1980) so that we cannot reliably separate interstellar and circumstellar components.

6. CONCLUSIONS

We confirm the suggestion of Volk & Cohen (1989a) that IRAS 17380−3031 (= WR98a) is a dusty WCL star, and emphasize the power of the "LRS technique" for seeking new dusty WCLs. Extensions of the Volk & Cohen (1989a) 40 Jy 12 μm flux-limited survey to 20 and then 10 Jy (Volk et al. 1990a, b) have revealed a handful of new potential dusty WCL candidates. We hope to pursue spectroscopy for those that have optical counterparts, particularly IRAS 18405−0448 (= WR120a?, WCL?), in order to augment the small sample of these objects currently known.

If episodes of fresh dust condensation in WCs recurred on time scales longer than that of the infrared fading due to expansion in the wind (which one might expect for stars with higher wind velocities—the WCEs), then the chances of finding circumstellar dust from a random observation of a given WC star would be reduced. In such a situation, *IRAS*-based searches for dusty WC stars could potentially uncover more examples of these intriguing systems.

We thank the ATAC and the Director, AAO for assigning time to this spectral observation of IRAS 17380−3031, and PATT for granting time for the two micron spectroscopy. We are most grateful to Raylee Stathakis for obtaining and reducing the AAO spectrum. We thank F. Spaan for securing the 1989 infrared photometry, and D. de Winter for that of 1990.

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