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THE HIGH-LATITUDE F SUPERGIANT IRAS 18095+2704: A PROTO–PLANETARY NEBULA[1]

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ABSTRACT

We report the discovery of a new high-latitude F supergiant, IRAS 18095+2704, which shows a large excess in the far-infrared. Ground-based observations have identified it as a $V = 10.4$ mag F3 Ib star which displays light and velocity variability. Comparison with the post-asymptotic giant branch (AGB) evolution model of Volk and Kwok suggests that it is an excellent candidate for a proto–planetary nebula. Model fitting of the spectrum of 18095+2704 from 0.35 to 100 μm suggests that it evolved from the AGB approximately 265 yr ago and had a mass-loss rate of 3×10^{-5} $M_\odot$ yr^{-1} at the end of the AGB.

Subject headings: infrared: sources — nebulae: planetary — stars: circumstellar shells — stars: evolution — stars: supergiants

I. INTRODUCTION

Recent studies have led to increasing evidence that a number of high-latitude F supergiants, the so-called 89 Her objects (Bond, Carney, and Grauer 1984; sometimes called UU Her objects, Sasselov 1983) are actually Population II post–asymptotic giant branch stars. Rather than being high-mass stars, they are low-mass objects which have lost most of their envelope mass in the asymptotic giant branch (AGB) phase. This evidence includes (*a*) large distance from the galactic plane, (*b*) high space velocity, and (*c*) low metal abundance (Bond and Luck 1987). More recently, evidence for circumstellar dust (Parthasarathy and Pottasch 1986) and molecular envelopes (Likkel *et al.* 1987) has strengthened the case for these being objects which have lost mass and are now in the post–AGB phase. Note, however, that all of these observational properties are not found in each member of this class.

Attention was first drawn to the high-latitude F supergiants by Bidelman (1951). The number of such stars known is presently small, with fewer than a dozen good candidates. These include 89 Her, HD 161796, HD 112374 (=HR 4912), HD 46703, UU Her, BL Tel (F component), HD 101584, and HD 187885 (=SAO 163075) (Bond, Carney, and Grauer 1984; Sasselov 1983; Parthasarathy and Pottasch 1986). These objects are F supergiants, and the better studied ones display low-amplitude light and velocity variability with periods of several weeks to months.

As part of a program to study AGB stars and proto–planetary nebulae (PPN), we have been observing candidates in the infrared with the Canada-France-Hawaii Telescope (CFHT; Kwok, Hrivnak, and Boreiko 1987*a*, *b*). Our ground-based data are combined with the *IRAS* photometry to produce infrared spectra, and the results are compared with radiative transfer models of AGB stars and PPN (Volk and Kwok 1988*a*, *b*). The theoretical models of PPN predict a steep slope of the continuum shortward of the 10 μm feature and a search of the *Catalog of Low Resolution IRAS Spectra* resulted in a number of sources showing agreement with the model prediction, one of them being IRAS 18095+2704. At the CFHT, we identified this source with a relatively bright star, whose optical properties we discuss in the next section. Figure 1 contains a finding chart for this object. The 1950.0 coordinates which we determined at the telescope are R.A. = $18^h09^m31^s.0$ and decl. = $+27°04'30''$, with an accuracy of $\pm 7''$. This is very close to the *IRAS* position. Its galactic coordinates are $l = 53°.8$, $b = +20°.2$. The object is not contained in the BD catalog, and we have not found it in any preexisting catalog.

In this paper, we present evidence to show that 18095+2704 is a member of this class of high-latitude F supergiants, discuss its properties, and argue that it is a good candidate for a proto–planetary nebula.

II. GROUND-BASED OBSERVATIONS

IRAS 18095+2704 was observed spectroscopically with the 1.8 m telescope at the Dominion Astrophysical Observatory (DAO). Two spectra were obtained in 1987 June with the DAO shectograph, which is a two-channel, photon-counting, intensified Reticon system, with one channel recording the star and the other sky. A third spectrum was obtained in 1987 August with a single-array Reticon detector. All were at a dispersion of 30 Å mm^{-1} and an effective resolution of 1.5 Å. A sky-subtracted shectograph spectrum of 18095+2704 is displayed in Figure 2. Note that the spectrum has not been flux calibrated and includes the shape of the detector response.

We classify the spectrum as about F3 Ib. This is based upon comparison with the photographic spectra in the atlas by Yamashita, Nariai, and Norimoto (1978) and comparison with Reticon spectra of 89 Her (F2 Ib) and HD 161796 (F3 Ib; Fernie and Garrison 1984) obtained with the same instrumentation on the last of the three observing nights. The object is less luminous and at a slightly lower temperature than 89 Her and is perhaps less luminous than HD 161796. Several radial velocity observations have kindly been obtained by D. West-

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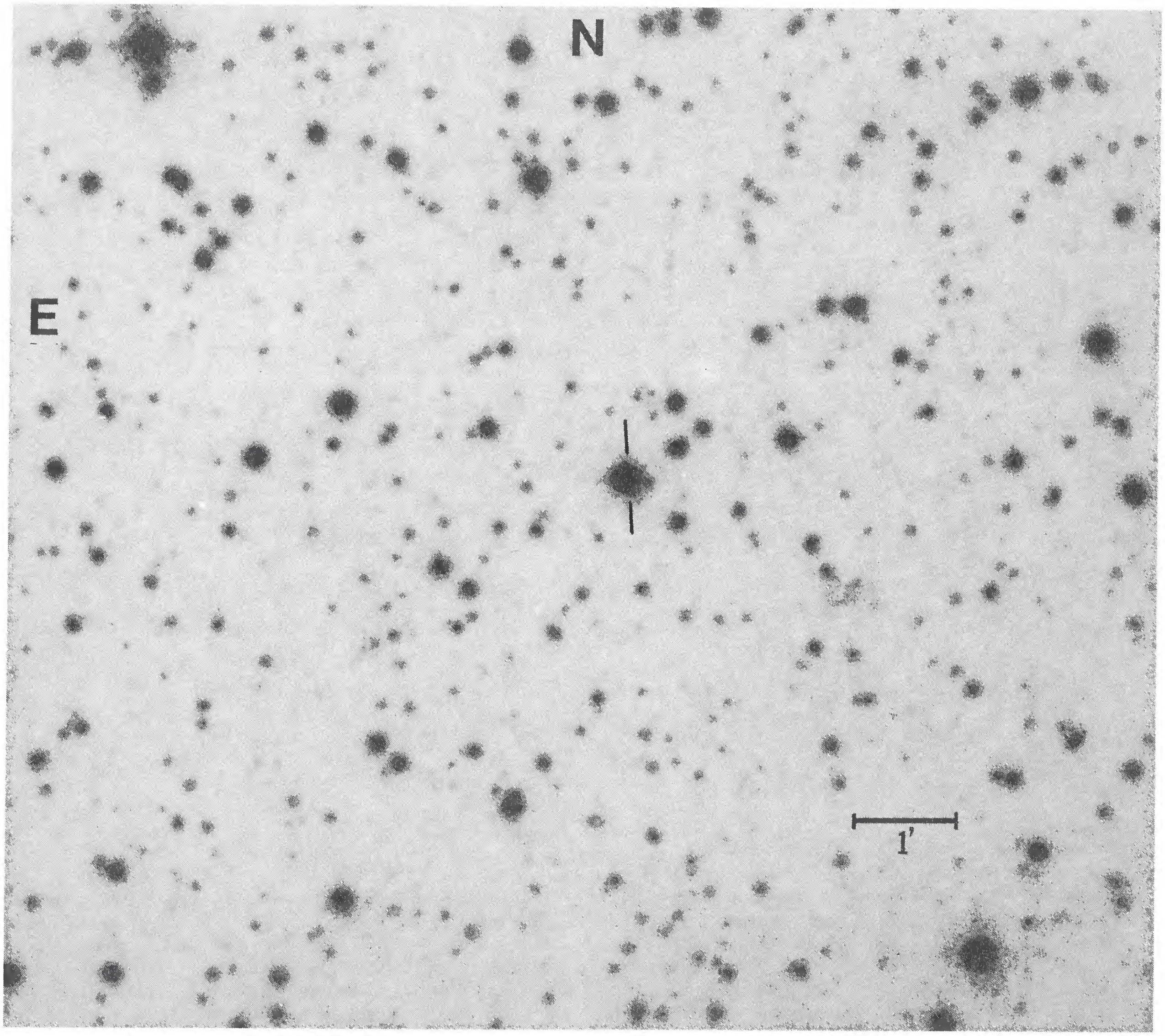

FIG. 1.—Finding chart for 18095+2704, reproduced from the Palomar Observatory Sky Survey red (E) print. The scale is indicated on the lower right. The 1950.0 coordinates are R.A. = $18^h09^m31^s.0$ and decl. = $+27°04'30''$.

pfahl and D. Welch with the DAO radial velocity spectrometer. These yield a mean heliocentric radial velocity of -30 ± 2 km s^{-1}, with an indication of variability.

Ground-based photometric observations have also been obtained. Intermediate-band *uvby* observations were undertaken by E. Olson and P. Etzel on three nights in 1987 June and July with the 1.0 m telescope at Mount Laguna Observatory. The *v* filter was nonstandard, centered 100 Å longward of the standard one. Differential photometry with respect to HD 161817 (Philip and Philip 1973) led to the mean magnitudes listed in Table 1 along with the standard deviations of a single observation. The object is variable in light with an observed range of 0.07 mag in *y*. The individual photometric observations, along with the individual radial velocity values, will be included as part of a longer term study of the variability of this object. Subsequently, one of us (B. J. H.) observed the object with the 0.6 m telescope at Yerkes Observatory, obtaining *B* and *V* magnitudes on the standard Johnson system. These are also listed in Table 1. A conversion to flux was accomplished for the *B* and *V* measurements using the calibration of Hayes (1979). The *uvby* flux conversion was performed by deriving the flux relative to that through the *y* band, following the procedures of Olson (1982) and based upon Kurucz (1979) model atmospheres for 6000 to 7000 K supergiants. The *y* band calibration was assumed to be the same as that of *V*, which is sufficiently close for our purposes. The object has an observed $(B-V)$ value of $+1.03$. Assuming that $(B-V)_0 = 0.25$, an average value derived from the tabulation of FitzGerald (1970) and Johnson (1966), yields $E(B-V)$ of 0.78. In comparison, the contribution from interstellar reddening in this region is esti-

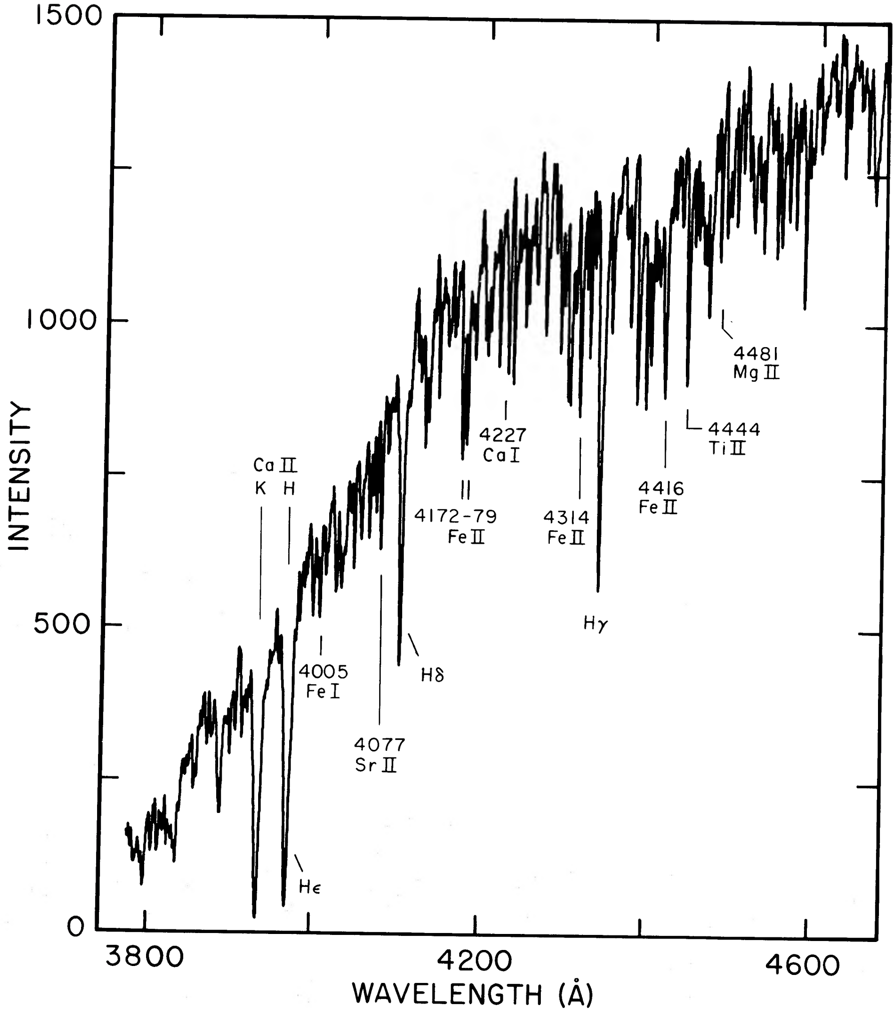

FIG. 2.—Optical spectrum of 18095+2704

mated to have a value of $E(B-V) = 0.11$ (Burstein and Heiles 1982). Thus most of the reddening must be circumstellar.

Mean Strömgren indices from the *uvby* measurements yield $(b-y) = 0.65$, $c_1 = 1.29$, and $m_1 = 0.10$. Again the indices indicate a large reddening. Dereddening the indices with an assumed $E(b-y) = 0.5$, slightly less than that which would be derived from transforming the above value of $E(B-V)$, yields $(b-y)_0 = 0.15$, $(c_1)_0 = 1.19$, and $(m_1)_0 = 0.25$. The color is appropriate for an early F star, and the $(c_1)_0$ index agrees with the high luminosity indicated by the spectrum. The $(m_1)_0$ index is anomalously high. However, since this object is heavily reddened, and most of the reddening is circumstellar with a different wavelength-dependence than the interstellar extinction, one might expect difficulty in appropriately dereddening the luminosity and metallicity indices based upon standard reddening relationships. Thus the dereddened Strömgren indices are consistent with the spectroscopically derived spectral and luminosity classes, but the m_1 index is anomalous.

The object was also observed in the near-infrared by F. Gillett at KPNO. The magnitudes are listed in Table 1 and were converted to flux using calibration factors provided by R. Joyce. Note that the M' filter used is fairly narrow, and critically sensitive to CO.

These ground-based observations, when combined with the *IRAS* observations discussed in the next section, provide us with a spectrum of the object ranging from 0.35 to 100 μm. Although the observations are not simultaneous, typical objects in this class vary in visible light by 0.1 mag with periods of several weeks to several months. IRAS 18095+2704 is not a previously known variable in the visible (Kholopov *et al.* 1982), and based upon the three epoch *IRAS* observations over a period of six months, it was assigned a 15% probability of variability. Thus the merger of all the data into a combined

TABLE 1

GROUND-BASED PHOTOMETRY OF 18095+2704

Date	JD	Magnitude				
A. Visible						
		u	v	b	$V(y)$	
1987 Jun 27–Jul 25	(3 nights)	13.84	11.74	10.99	10.34	
		±0.07	±0.08	±0.06	±0.04	
				B	V	
1987 Sep 3	2,447,041			11.46	10.43	
B. Infrared						
		J	H	K	L	M'
1986 Jul 11	2,446,622	7.52	6.86	6.47	5.87	4.99

NOTE.—Observational uncertainties are 0.04 mag in B and V, 0.03 mag in J, H, K, L, and 0.12 mag in M'.

spectrum appears justified, within an accuracy of about 10%. The combined visual and infrared spectrum from 0.35 to 100 μm is shown in Figure 3. The plotted data have been corrected in the visible and near-infrared to account for interstellar extinction, using the average extinction curve of Savage and Mathis (1979) and $E(B-V) = 0.11$.

III. IRAS OBSERVATIONS

IRAS 18095+2704 was detected by the *IRAS* low-resolution spectrometer (LRS) and is classified as type 69, a star with the 10 μm silicate feature in emission on a red continuum. Figure 3 shows the combined *IRAS* spectral and photometric measurements. The *IRAS* broad-band measurements are taken from the *IRAS* Point Source Catalog and have been corrected for color using the procedure described in Kwok, Hrivnak, and Milone (1985). The steep slope of the short wavelength side of the LRS spectrum was noted by Volk and Kwok (1987), who suggested that such a peculiar spectral shape could be the result of a detached dust shell.

We suggest that the far-infrared component between 10 and 100 μm is due to emission from the remnant of the circumstellar dust shell which detached at the tip of the AGB, and the component shortward of 7 μm is due to photospheric emission of the central star which is now evolving leftward in the H-R diagram and gradually emerging from this dust shell. Such a dual-peak, spectral behavior for PPN is also discussed by Habing, van der Veen, and Geballe (1987). In Figure 3 is also plotted the result of a dust radiative transfer model. The model spectrum is produced by assuming an $r^{-2.5}$ dust density profile with an inner radius of 5.8×10^{15} cm. The central star is assumed to have a photospheric temperature of 7000 K and a luminosity of 6000 $L_\odot$. The dust opacity function is the same one derived for AGB stars by Volk and Kwok (1988*a*). This model is normalized to fit the infrared spectrum of the object. The agreement in the infrared is excellent, both in the fit to the overall shape and the fit to the 10 μm silicate feature. At near-infrared and visible wavelengths, the model has approximately the correct shape, but the observations fall below the predicted curve, deviating monotonically by an increasing amount at shorter wavelengths.

The visible and near-infrared flux can be fitted by adding a λ^{-1} extinction component. This is shown by the dotted line in Figure 3. At the high galactic latitude of this object, it is unlikely to be due to interstellar extinction, but presumably indicates an additional component to the circumstellar dust. Such a λ^{-1} component was also invoked by Lamers *et al.* (1986) to explain a short wavelength deficiency in the observed flux spectrum of HR 4049, a B9.5 supergiant which they suggest may also be a PPN. Note that Lamers *et al.* fitted a blackbody curve to the infrared spectrum and independently

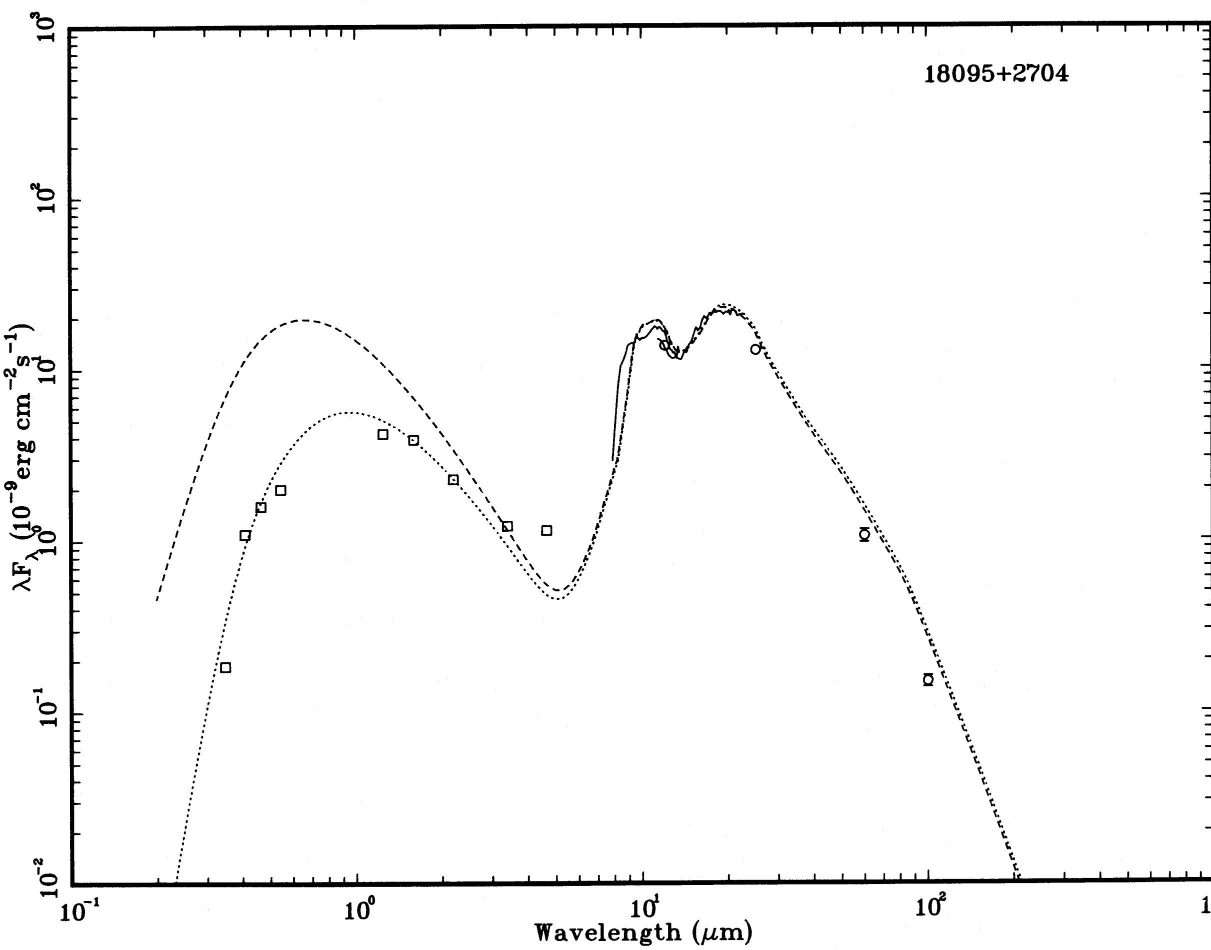

FIG. 3.—The *IRAS* LRS spectrum of 18095+2704 combined with the ground-based and *IRAS* photometry, and plotted together with a PPN model. The temperature, luminosity, and distance are assumed to be 7000 K, $6 \times 10^3 L_\odot$, and 1.9 kpc, respectively. Dotted line shows the resultant spectrum after the inclusion of an extinction component of the form exp $[-1.072/\lambda(\mu\mathrm{m})]$.

fitted a model atmosphere normalized at V to the visible flux distribution. This resulted in a deficiency in the observed ultraviolet flux. In our model, we have fitted the results of a dust radiative transfer model to the infrared spectrum and *predicted* theoretically the visible and near-infrared energy distribution. The use of one consistent model for both the infrared and visible spectrum results in the need for the additional λ^{-1} component throughout the spectrum. We interpret this component as evidence for a more extended dust shell farther from the star.

One of the mysteries of these F supergiants has been the combination of strong infrared excess with a bright optical object (Humphreys and Ney 1974). This can be explained by the PPN model because the dust emission originates a large distance from the star and causes far less extinction in the visible than in the case of M stars on the AGB. The fact that the observed visible and near-infrared spectrum has the same shape as the model confirms that the stellar photospheric continuum is responsible for emission in these wavelength regions. While we cannot rule out the possibility that this object is a high-mass star making a blueward loop on the H-R diagram after a mass-losing episode as a red supergiant, the high galactic latitude of the object and the excellent agreement between the theoretical and observational results gives us great confidence that 18095+2704 is indeed a PPN.

IV. CIRCUMSTELLAR OH EMISSION

OH maser emission was detected from 18095+2704 at 1612 and 1665/67 MHz from Arecibo (Lewis, Eder, and Terzian 1985; Eder, Lewis, and Terzian 1988). They determined $V_{\rm LSR} = -4.6$ km s^{-1} and $\Delta V = 13.6$ km s^{-1}. The flux ratio of the two peaks is 1.4, consistent with a uniformly expanding shell. Lewis, Eder, and Terzian (1985) noted that the 1612 MHz flux was much weaker than the signal at both 1665 and 1667 MHz. The weakness of the 1612 MHz line is unusual for an OH/IR star with such a low color temperature. In a model of OH emission in AGB stars, Sun and Kwok (1987) suggest that OH emission can be detected, although with decreasing strength, for $\sim$1000 yr beyond the AGB into the PPN phase. This weakness of the 1612 MHz line is therefore consistent with 18095+2704 being a PPN. Zuckerman and Lo (1987) failed to detect H_2O maser emission from 18095+2704 and set an upper limit for line flux at 0.3 Jy. This is also consistent with the detached shell picture, for H_2O emissions are generally assumed to be generated in the high-density circumstellar region near the star. IRAS 18095+2704 was observed by O. Aaquist and S. Kwok on 1986 April 14 with the Very Large Array in the "A" configuration. An upper limit of 1 mJy is placed on the λ6 cm continuum emission.

The stellar velocity inferred from OH observations can be compared with that obtained in the optical region (§ II). Transforming the local standard of rest (LSR) OH velocity to a heliocentric velocity leads to V(OH) $= -17.4$ km s^{-1}, a difference of 12 km s^{-1} from the mean V(optical). Radial velocity observations of 89 Her and HD 161796 reveal peak-to-peak variations of 8 and 12 km s^{-1} respectively, with a quasi-periodic behavior (Burki, Mayor, and Rufener 1980), and for HD 101584 a velocity range of 20 km s^{-1} has been observed (Humphreys and Ney 1974). Since the OH velocity is generally accepted as a better representation of the stellar velocity, this difference in velocity is presumably due to atmospheric variations similar to that of other F supergiants.

The OH linewidth of 13.6 km s^{-1} implies a wind velocity of $\sim$7 km s^{-1}. From the model derived inner radius of 5.8×10^{15} cm, we can estimate that 18095+2704 is approximately 265 yr beyond the AGB and the mass-loss rate at the tip of the AGB was $3 \times 10^{-5}\ M_{\odot}$ yr^{-1}.

V. CONCLUSIONS

Theoretical models suggest that PPN with oxygen-rich progenitors should show a steep continuum shortward of the 10 μm silicate feature, and a search of the *IRAS* LRS catalog led to the identification of 18095+2704 as a possible candidate. Ground-based observations in the visible and near-infrared confirm the theoretical predictions and indicate that the central star has emerged from the thick dust envelope created during the AGB phase. Spectroscopic observations suggest a present spectral type of F3 Ib, consistent with the spectral type of an object in transition between the AGB and the planetary nebula phase. We expect that the spectral class of 18095+2704 will evolve rapidly, and further observations in the next few decades to detect such variations would be extremely valuable in our understanding of the formation of planetary nebulae.

While the number of candidates for PPN is small at present, a number of new candidates, in addition to the F supergiants listed in § I, have been identified by Volk and Kwok (1988*b*) based upon their *IRAS* LRS or colors. We are presently studying some of these additional individual sources in detail to better elucidate this important stage in stellar evolution.

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REFERENCES

Bidelman, W. P. 1951, *Ap. J.*, **113**, 304.
Bond, H. E., Carney, B. W., and Grauer, A. D. 1984, *Pub. A.S.P.*, **96**, 176.
Bond, H. E., and Luck, R. E. 1987, in *IAU Colloquium 95; The Second Conference on Faint Blue Stars*, in press.
Burstein, D., and Heiles, C. 1982, *A.J.*, **87**, 1165.
Burki, G., Mayor, M., and Rufener, F. 1980, *Astr. Ap. Suppl.*, **42**, 383.
Eder, J., Lewis, B. M., and Terzian, Y. 1988, *Ap. J. Suppl.*, **66**, 183.
Fernie, J. D., and Garrison, R. F. 1984, *Ap. J.*, **285**, 698.
FitzGerald, M. P. 1970, *Astr. Ap.*, **4**, 234.
Habing, H. J., van der Veen, W., and Geballe, T. 1987, in *The Late Stages of Stellar Evolution*, ed. S. Kwok and S. R. Pottasch (Dordrecht: Reidel), p. 91.
Hayes, D. S. 1979, *Dudley Obs. Rept.*, **14**, 297.
Humphreys, R. M., and Ney, E. P. 1974, *Ap. J.*, **190**, 339.
Johnson, H. L. 1966, *Ann. Rev. Astr. Ap.*, **4**, 193.
Kholopov, P. N., *et al.* 1982, *New Catalog of Suspected Variable Stars* (Moscow: Nauka).
Kurucz, R. L. 1979, *Ap. J. Suppl.*, **40**, 1.
Kwok, S., Hrivnak, B. J., and Milone, E. F. 1985, *Ap. J.*, **303**, 451.

Kwok, S., Hrivnak, B. J., and Boreiko, R. T. 1987*a*, *Ap. J.*, **312**, 303.
———. 1987*b*, *Ap. J.*, **321**, 975.
Lamars, H. J. G. L. M., Waters, L. B. F. M., Garmany, C. D., Perez, M. R., and Waelkens, C. 1986, *Astr. Ap.*, **154**, L20.
Lewis, B. M., Eder, J., and Terzian, Y. 1985, *Nature*, **313**, 200.
Likkel, L., Omont, A., Morris, M., and Forveille, T. 1987, *Astr. Ap.*, **173**, L11.
Olson, E. C. 1982, *Ap. J.*, **257**, 198.
Parthasarathy, M., and Pottasch, S. R. 1986, *Astr. Ap.*, **154**, L16.
Philip, A. G. D., and Philip, K. D. 1973, *Ap. J.*, **179**, 855.
Sasselov, D. D. 1983, *Inf. Bull. Var. Stars*, No. 2314.
Savage, B. D., and Mathis, J. S. 1979,, *Ann. Rev. Astr. Ap.*, **17**, 73.
Sun, J., and Kwok, S. 1987, *Astr. Ap.*, **185**, 258.
Volk, K. M., and Kwok, S. 1987, in *The Late Stages of Stellar Evolution*, ed. S. Kwok and S. R. Pottasch (Dordrecht: Reidel), p. 305.
———. 1988*a*, *Ap. J.*, submitted.
———. 1988*b*, in preparation.
Yamashita, Y., Nariai, K., and Norimoto, Y. 1978, *An Atlas of Representative Stellar Spectra* (New York: Wiley).
Zuckerman, B. and Lo, K. Y. 1987, *Astr. Ap.*, **173**, 263.

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