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THE UNIQUE COMETARY NEBULA PARSAMIAN 13[1]

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ABSTRACT

Parsamian 13 is found to be a cometary nebula, with a deeply embedded star suffering strong absorption by silicate grains. A feature near 2.7 μm, attributed to absorption by terminal OH groups, may represent the first detection in an astrophysical environment of water ice grains diluted by another molecule, for example by CO. The bolometric luminosity suggests that this star is either an extremely young T Tauri star or an evolved low-mass star, now a red giant, high on its convective track. Most unusual is the presence of cold (50 K) TiO gas in sufficient abundance to show in absorption in the optical and very near-infrared regions; this material probably represents very recently expelled photospheric layers.

Subject headings: interstellar: grains — interstellar: molecules — nebulae: abundances — nebulae: individual — stars: pre-main-sequence

I. INTRODUCTION

As part of an ongoing study of cometary nebulae and their associated stars, observations have been made of object 13 in Parsamian's (Parsamian and Petrossian 1979) recent list. On the National Geographic Society-Palomar Observatory Sky Survey photographs this object appears to consist of two well-separated components (Fig. 1). The southern is a very red nebula some 17″ in extent with a parabolic northern boundary whose vertex is closest to the northern component. The northern component lies on the axis of this parabola. The northern object is quite faint, very red, and appears to be stellar.

This paper describes optical spectrophotometry, ground-based infrared broad-band photometry of both components, and airborne far-infrared photometry; also 2–4 μm and 8–13 μm narrow-band spectrophotometry of the infrared source associated with the southern object. On the basis of these data, the southern component is a cometary nebula with a bright infrared object at its apex. Its embedded star is optically not directly visible but is seen through the plane of an edge-on dust disk that produces ice and silicate absorption features. Deep absorption features due to neutral metals (Ca, Mg, Na, K) and to cold (≈ 50 K) TiO molecules arise along the indirect path to the star, via the fan nebula. It is suggested that this dense cold matter has been ejected from the embedded star, which may be either a cool (M type) T Tauri star high on its convective track, or an evolved low-mass ($\approx 1\ M_\odot$) M giant undergoing substantial mass loss on its way to becoming a planetary nebula.

The northern component is a cool T Tauri star apparently not physically related to P13S (in spite of its location on the axis of the parabolic nebula), although lying in the same dark cloud.

[1]Observations obtained in part using the facilities of the Lick Observatory, California.

II. OBSERVATIONS

a) *Optical Spectroscopy*

Optical spectra were obtained on 1980 December 1 and 15 using the Cassegrain image-tube scanner on the Lick Observatory 3 m telescope. The useful regions covered on each night were λλ4250–6800, 6250–8500 with effective resolution ≈10 Å. Apertures 2″.7 by 4″ were used, with long axes oriented east-west. Data were reduced to absolute fluxes through observations of Lick standard stars (Stone 1974). Figures 2 and 3 present the 1980 December 15 yellow and red spectra of P13N and P13S in the form of F_ν against λ.

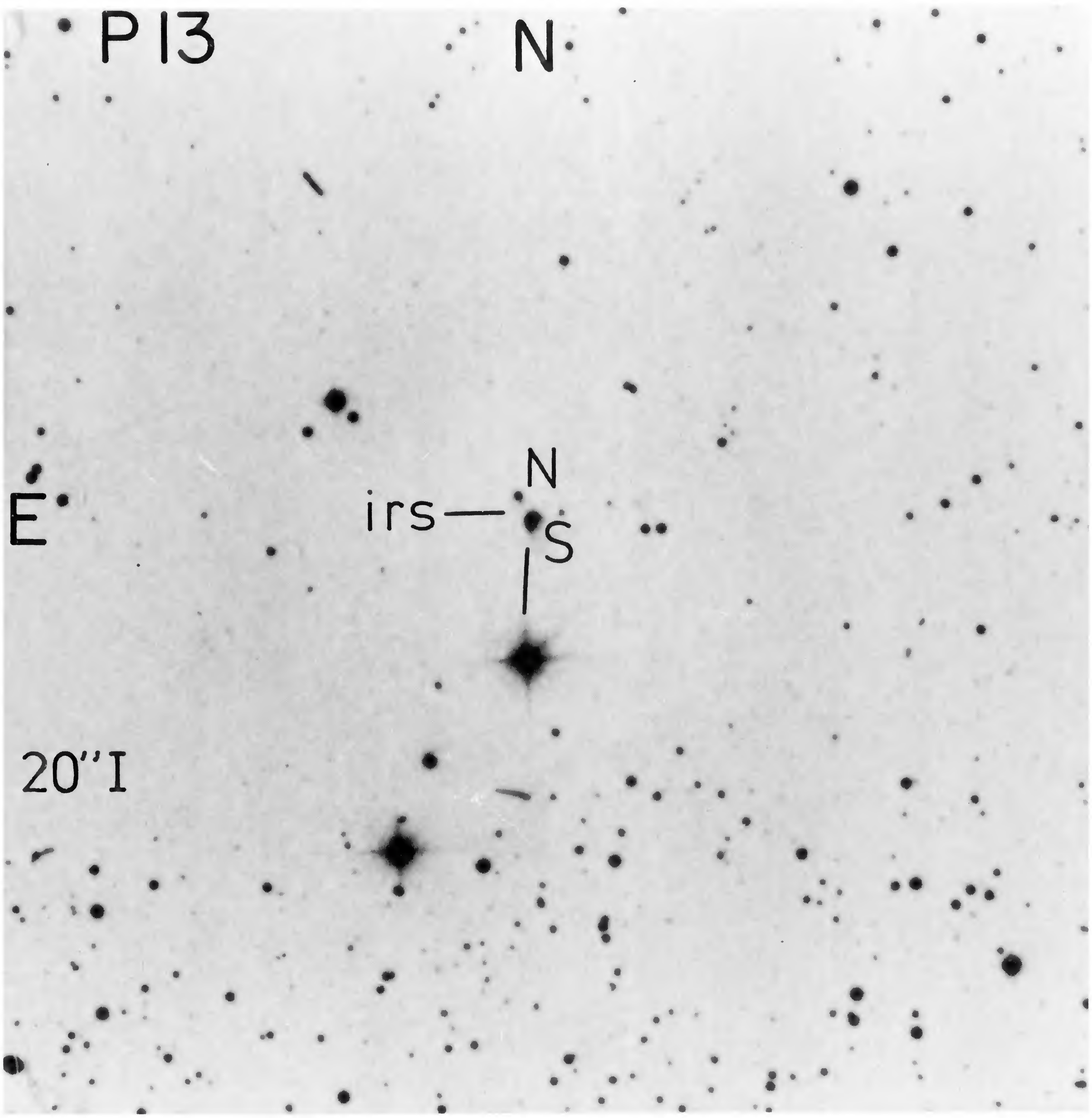

FIG. 1.—Parsamian 13, reproduced from the NGS-PO Sky Survey photograph, showing the N and S components and the location of the infrared sources (irs) in P13S.

b) *Infrared Photometry*

Broad-band infrared photometry of P13N and P13S was obtained with the 3.8 m UKIRT on 1981 October 16 and 18, and with the KPNO 1.3 m telescope on 1981 December 10. Table 1 presents these data in the form of mean magnitudes with total 1 σ-of-the-mean errors in parentheses.

Astrometry with respect to two nearby SAO stars (2′ and 5′ distant) with both telescopes yielded the following positions (equinox 1950) for both the 2 and 10 μm emission peaks of P13S, and the 2 μm emission of P13N:

P13S $04^{h}07^{m}20\overset{s}{.}93 \pm 0\overset{s}{.}15$; $+38°00′\ 7″ \pm 1″$

P13N $04\ 07\ 21.65 \pm 0.2$; $+38\ 00\ 23\ \pm 3$.

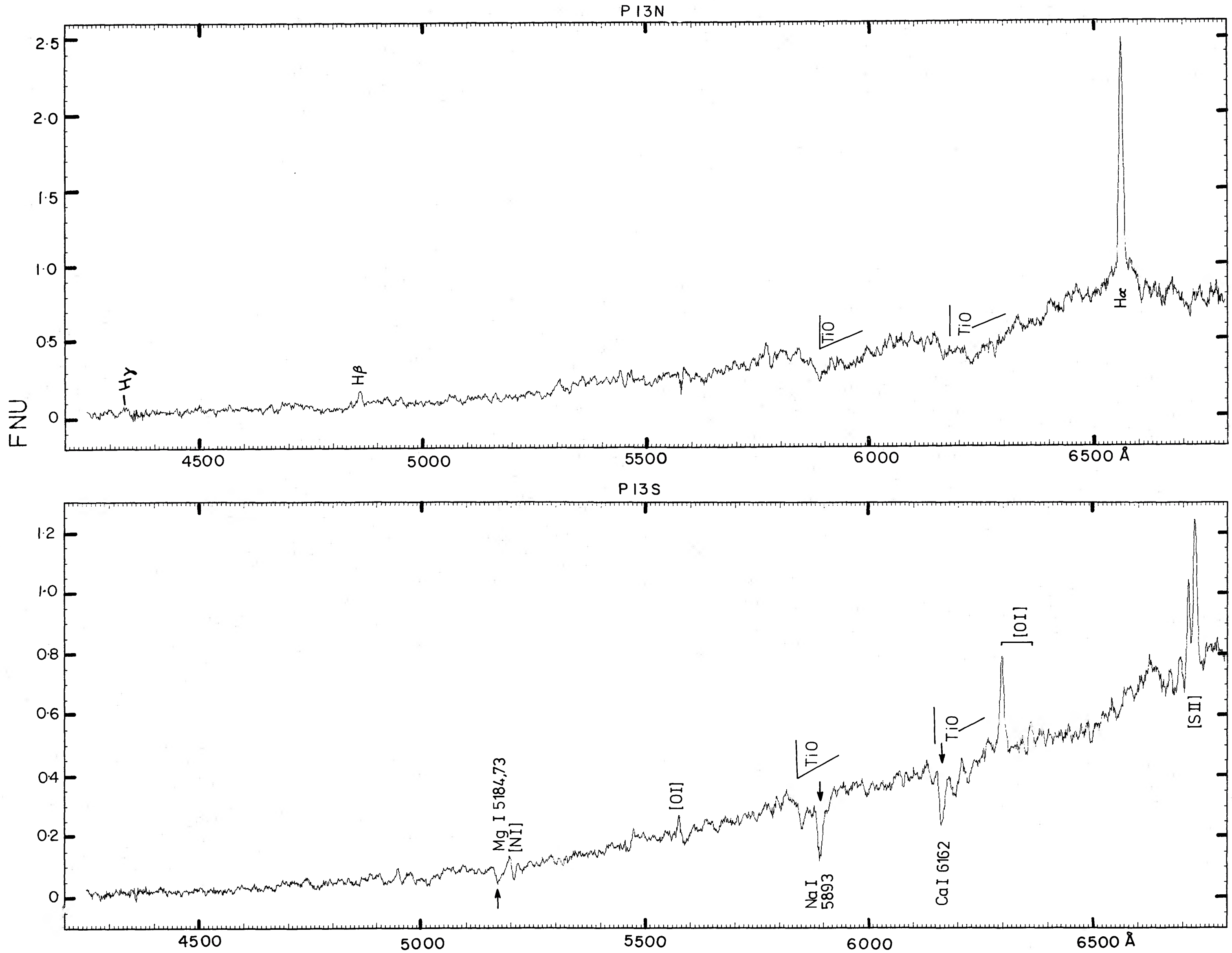

FIG. 2.—Yellow spectra of P13N and P13S. Principal emission features are marked, as are the TiO absorptions in P13N, and the strong neutral metal lines in P13S. Ordinates are F_ν in ergs cm^{-2} s^{-1} Hz^{-1}; scale units are 1.0E-26 for both P13N and S.

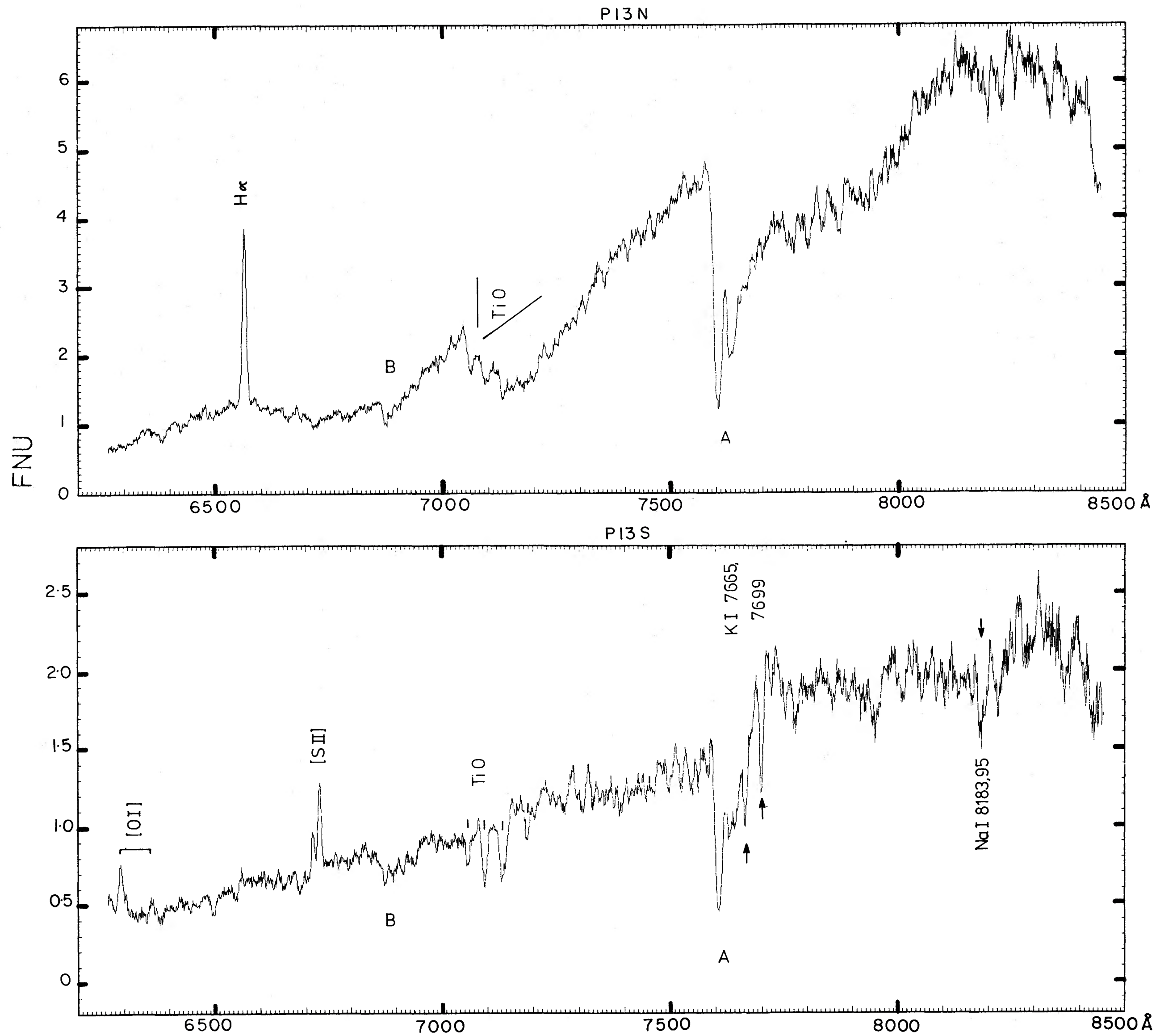

FIG. 3.—Red spectra of P13N and P13S. "A" and "B" denote deep terrestrial oxygen absorption bands. Neutral sodium and potassium features are indicated in P13S. Ordinates and scale units are as in Fig. 2.

TABLE 1

GROUND-BASED INFRARED PHOTOMETRY OF P13

a) UKIRT magnitudes; 1-σ-of-the-mean errors in magnitudes parenthesized

Effective wavelength (μm)	[1.25]	[1.65]	[2.2]	[3.8]
FWHM (μm)	0.29	0.30	0.42	0.68
Component				
P13N	12.48(01)	11.31(01)	10.60(03)	10.38(28)
P13S	12.47(01)	10.67(02)	8.52(01)	5.50(01)

b) KPNO magnitudes for P13S; errors parenthesized as above

Effective wavelength (μm)	[2.2]	[3.45]	[4.6]	[8.4]	[9.6]	[10.1][a]	[10.2][b]	[11.0]	[12.5]	[19]
FWHM (μm)	0.42	0.57	0.34	1.6	1.6	0.4	6	1.7	1.7	cut-on 18 μm
Magnitude	8.54(10)	5.73(04)	4.17(06)	2.49(03)	3.30(08)	3.03(14)	2.39(03)	2.43(06)	1.43(04)	−0.34(06)

[a] Narrow-band filter.
[b] Broad-band filter.

Measurements on the POSS photographs indicate that the infrared source in P13S lies at the northern apex of the parabolic nebula (Fig. 1).

c) *Airborne Far-Infrared Photometry*

Broad-band far-infrared photometry of P13 was acquired from the Kuiper Airborne Observatory (KAO) on 1982 November 24. P. Harvey's photometer was used with six bolometers yielding three 50″ FWHM beams, separated ±1′ in azimuth from the central aperture, and simultaneous measurements of flux at two different wavelengths. The central wavelengths of the broad filters were 50, 65, 100, 130, and 160 μm. Absolute flux calibration was with respect to NGC 7027 and GL 490, and extinction corrections were applied based upon the amounts of precipitable water vapor measured from the KAO during the observations.

Table 2 presents the far-infrared fluxes (in Jy) with errors representing the statistical uncertainties in the photometry to which should be added uncertainties in the absolute calibration of about ±15%.

Figure 4 shows the overall spectral energy distribution of P13S.

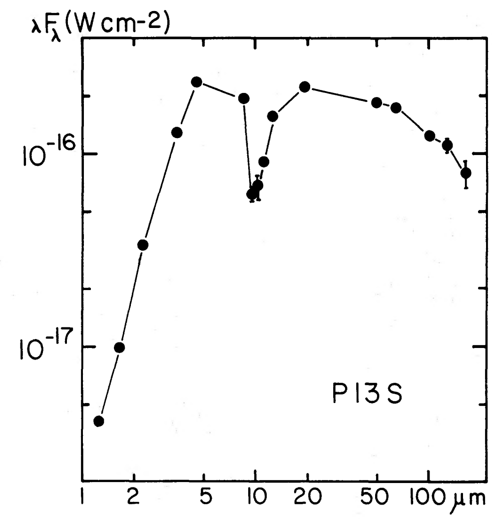

FIG. 4.—Overall energy distribution for P13S from 1.2 to 160 μm, combining ground-based infrared photometry (Table 1*a* and 1*b*) and airborne far-infrared data (Table 2).

III. INFRARED SPECTROPHOTOMETRY OF P13S

The 2.3–3.7 μm spectrum (Fig. 5) was observed through a 12″ aperture and a 1% resolution filterwheel in a UKIRT common-user photometer on 1981 November 15. Flux calibration and correction for atmospheric transmission were carried out using similar observations of 50 Persei. Chopping and beam-switching were performed in the east-west direction to avoid possible contamination from P13N. The flux distribution between 2.2 and 8.6 μm determined from the broad-band photometry (excluding that at *L* which is depressed by the ice absorption) is well-fitted by a 675 K blackbody curve which also fits the ends of the 3 μm spectrum. To form the normalized absorption profile (Fig. 6), we interpolated the observed spectrum using a 675 K blackbody flux distribution to represent that of the underlying source. The normalized absorption profile is qualitatively similar to those presented by Merrill, Russell, and Soifer (1976) in that it shows a long wavelength wing, but it is shifted to shorter wavelengths by about 0.05 μm. The optical depth at 3 μm is 1.6.

TABLE 2

FAR-INFRARED FLUXES OF P13S

λ(μm)	50	65	100	130	160
S_ν(Jy)	31±1.5	37±2	41±2	48±4	42±7

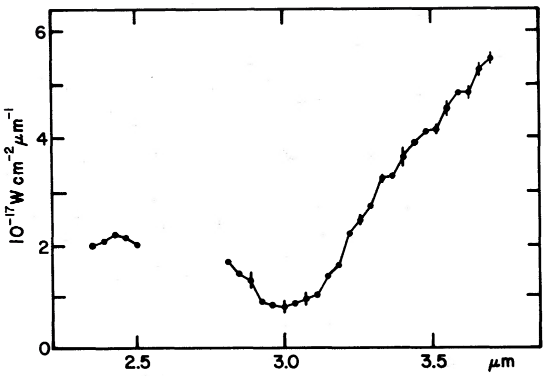

FIG. 5.—Near-infrared spectrophotometry for P13S showing the deep broad feature near 3 μm.

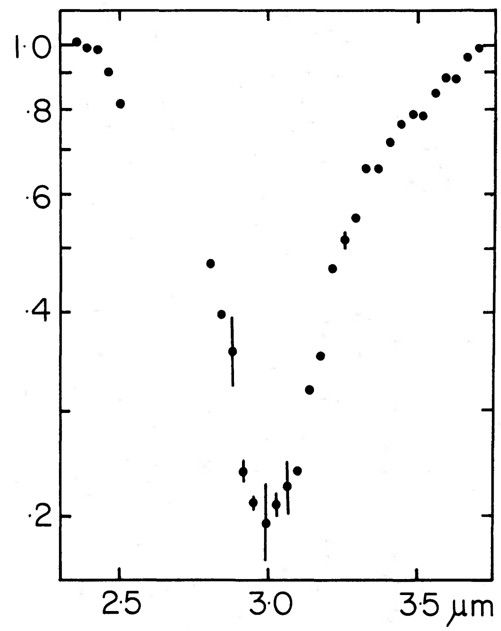

FIG. 6.—Normalized profile of the 3 μm feature in P13S. Ordinate is F_λ(P13S)/F_λ (675 K blackbody).

However, the structure of the 3 μm feature in P13S seems unique among astrophysical spectra in having such substantial absorption in the 2.5–2.8 μm region. This shortward feature can arise from mixtures of H_2O and CO as the dilutant, CO, is increased in concentration; it is ascribed to terminal OH groups by Hagen, Tielens, and Greenberg (1983*a*) who have investigated it in the laboratory.

At first glance, one might compare the 3 μm spectrum of P13S with that of OH 0739–14 (Gillett and Soifer 1976), a nebulous M9 III star (Cohen 1981). However, one has to be very careful to distinguish photospheric from circumstellar absorption features. Allen *et al.* (1980) presented a 2–2.5 μm spectrum of OH 0739–14 showing a strong stellar (gaseous) CO depression in this object. New unpublished spectropolarimetry of this source (Tielens 1983, private communication) confirms this 2.3 μm feature to be photospheric while the 3 μm feature is circumstellar. Further, a careful analysis of the Gillett and Soifer data for OH 0739–14 (Hagen, Tielens, and Greenberg 1983*b*) reveals no evidence of a high frequency wing that might be caused by CO–diluted water-ice. It is, therefore, our opinion that P13S is the first astrophysical source to show this high frequency wing.

The 8–13 μm spectrum was obtained on 1981 October 17 at the IRTF, using a multidetector grating spectrometer with a 5\".9 aperture. Calibration was via α Ceti. The 10 μm spectrum can be adequately fitted with a simple model of a 450 K blackbody suffering extinction by cold silicate grains, yielding $\tau(9.7\ \mu\text{m}) = 2.3$ and $\chi^2/N = 1.8$. A combination of a Planck function and silicate emission at a similar temperature, extinguished by silicate dust, improves the fit somewhat, producing $\tau(9.7\ \mu\text{m}) = 3.7$ and $\chi^2/N = 1.3$. This model suggests that some of the silicate dust is close to the star; this fit is shown in Figure 7. Using a value of $A_V/\tau(9.7\ \mu\text{m}) = 15$, these model fits indicate a visual extinction in the range $A_V \approx 30$–50 mag.

The ratio of depths in the "ice" and the 9.7 μm features is 0.7 for the first model considered above, the same as that found for the material in front of NGC 2024#2 and the BN object by Merrill *et al.* using the same model (their #I) for the silicate absorption. This suggests that we are seeing P13S through molecular cloud material of similar composition. The survival of the ice indicates that this absorbing material is primordial and not produced by mass loss from P13S.

IV. DISCUSSION

a) *Lynds 1473*

P13 appears to lie within a small dark cloud, Lynds 1473. The available colors of nearby bright stars indicate only that this cloud lies more than some 140 pc from the Sun (principally from photometry of HD 25975 and 26702: cf. Blanco *et al.* 1968). Lynds 1473 was observed in CO by Baran (1982) as part of his wide-beam microwave emission survey of Perseus and Taurus. J. Bally has also kindly obtained ^{12}CO and ^{13}CO observations of this cloud for us with the Bell Labs. 7 m antenna. The average velocity of these emission peaks in the direction of P13 ($l = 160.5$, $b = -9.8$) is -3.3 km s^{-1}, whence the distance would be 350 pc, if this represented a circular velocity. We therefore adopt this distance for both P13N and P13S.

b) *P13N*

The spectra of the northern component clearly refer to a cool star on the basis of the absorption bands of

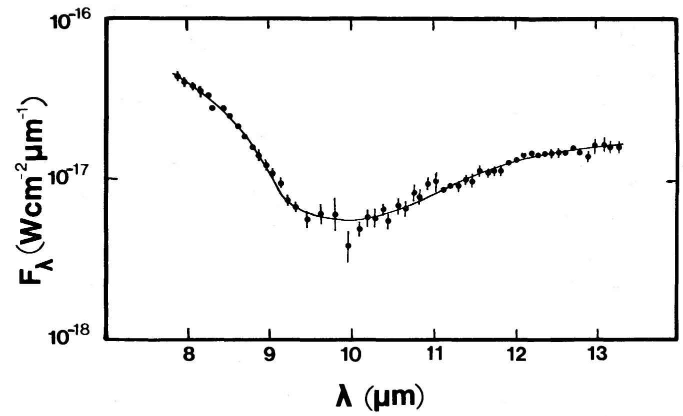

FIG. 7.—Ten μm spectrum of P13S and the model fit using warm silicate emission extinguished by overlying cold silicate grains

TiO. From the depths of several of these between 4900 and 7100 Å (Cohen and Kuhi 1976; Cohen 1981) the star is of type M2.5, and the lack of conspicuous CaH λ6385 absorption suggests a luminosity class of III or "IV" (see Cohen and Kuhi 1979). Hα emission is strongly present with an equivalent width of around 18 Å. The intensity ratio, $I(\mathrm{H}\alpha)/I(\mathrm{H}\beta)$, is 9.3 from the yellow spectrum on December 15. Although the signal-to-noise ratio is poor, Hγ may be weakly present in emission in this spectrum (Fig. 2). An estimate of the intensity ratio, $I(\mathrm{H}\beta)/I(\mathrm{H}\gamma)$, is more than 1.2. From this limit to the approximate Balmer decrement we find that the extinction of the emitting zone is less than about 0.9 mag, assuming that the lines arise by radiative recombination.

Narrow-band continuum color indices between 5400, 5800, and 6536 Å, between 7045 and 7570 Å, and between 6536 and 8200 Å indicate a photospheric extinction of 1.3 ± 0.2 mag, compared with the intrinsic colors of standard stars observed with the image-tube scanner (Cohen and Kuhi 1976; Cohen 1981). It appears that photosphere and emission-line zone suffer the same extinction of about 1 mag.

The spectral type, presence of strong Hα emission, and location apparently within a dark cloud suggest in combination that P13N is a T Tauri star. A distance of 350 pc, V of 17.9 (from the scanner spectrophotometry), and A_V of 1.3 (derived above) indicate an M_V of 8.9, comparable with the absolute magnitudes of early M-type T Tauri stars in the Taurus-Auriga dark clouds (Cohen and Kuhi 1979). The bolometric luminosity of P13N is 0.46 $L_\odot$ at this distance, also in keeping with values for typical T Tauri stars.

c) *P13S*

This object is purely nebulous through the guiding TV on the 3 m telescope. Its yellow spectrum reveals TiO absorptions that seem to mimic those of P13N, at λλ5862, 6159, although in P13S the heads are more sharply defined. P13S shows prominent emission of [O I] and [S II], and possibly of weak [N I], yet no Hα is seen. Collisional excitation of these forbidden lines would be consistent with a model for cometary nebulae in which a wind from the embedded infrared source/star produced the structure of P13S either by constraint from an equatorial disk surrounding the star (cf. Calvet and Cohen 1978; Cohen *et al.* 1981; Barral and Canto 1981), or by means of supersonic expansion through a de Laval nozzle (Königl 1982). Both the equivalent widths of the red [O I] and [S II] lines and the intensity ratio of the sulfur doublet have shown variations between December 1 and 15. These suggest the unsteady character of the stellar wind. In particular, $I(6717)/I(6731)$ was 0.38 ± 0.01 on December 1 and 0.52 ± 0.01 on December 15; ratios indicative of vastly different electron densities ($N_e \approx 3 \times 10^5$ and 1×10^4 cm^{-3}, respectively) and substantially in excess of the likely errors of measurement.

P13S, however, offers some remarkable clues to the nature of the material in this directed stellar wind. There are several striking features in the optical spectrum of P13S: the great strengths of neutral metal absorption lines, the highly curious appearance of the $\Delta v = 0$ sequence (near 7100 Å), and the seeming absence of the $\Delta v = +1$ sequence (near 7600 Å) of the TiO γ-system (cf. the spectrum of P13N, Figs. 2 and 3). It is rather difficult to disentangle metal lines from TiO in some cases since several of the suggested atomic lines would be indistinguishable at our resolution from TiO absorptions; for example, Mg I λλ5167, 5173, 5184 and TiO λλ5167, 5169 (0,0) α; Ca I λ6162 and TiO λ6162 (0,0) γ, λ6159 (1,4) α. However, the "Na I" and "K I" features lie far enough away from adjacent TiO heads that their identifications are secure.

We have attempted to synthesize the appearance of the $\Delta v = 0$ TiO triplet heads using model calculations kindly supplied by J. G. Phillips (molecular data for the models were taken from Phillips [1973], and the spectrum was degraded to the resolution of the Lick scanner). A temperature of 50 K suffices to reproduce the depths of the λλ7088, 7125 heads although no entirely satisfactory match can be found for the λ7054 head. This latter feature appears somewhat weaker than calculations imply. The determination of temperature is likely to be correct to the order of a factor of 2.

Strong neutral metal lines occur throughout the spectrum of P13S: the resonance lines of Na I (λλ5890, 5896) and K I (λλ7665, 7699); the interlocked triplet of Mg I (λλ5167, 5173, 5184), and subordinate lines of Na I (λλ8183, 8195) and of Ca I (λλ5589, 5599, 6162). From the equivalent widths of these absorption lines one can estimate the column densities of absorbers. Crude estimates yield numbers of order 1×10^{14} (Mg), 2×10^{13} (Na), 1×10^{13} (K), and 5×10^{13} (Ca) atoms cm^{-2}. The absence of these features toward P13N suggests that they do not arise in the interstellar medium, nor inside Lynds 1473, but rather between the nebulosity of P13S and the embedded star. This dense material must represent ejecta from this star.

Metal lines this strong, and the appearance of the λ7100 region, where the triplet TiO heads seem to have collapsed to the lines arising only from low J levels, betray the presence of a substantial column density of cold material. This probably represents gas, carried away from a stellar photosphere by a wind, that has cooled as it has moved outward into the nebula. In the λ5900 and λ6200 regions, the same sharpening of the TiO absorption structure is apparent. The heads are closer together in the yellow, and the flux levels between them do not achieve those of the adjacent continuum as is the case in the red.

There is precedent for nonphotospheric neutral metal lines in other cometary nebulae. For example, in the bipolar system V645 Cygni (= GL 2789; Cohen 1977), the sodium absorption deepens as the stellar spectrum is viewed by reflection from more and more distant material. In the fan nebula PV Cephei (Cohen *et al.* 1981), strongly variable sodium absorption was interpreted as due to fluctuations in the amount of material recently shed by a T Tauri star, and lying along the indirect line of sight to this star via the nebula. Only one other system reveals persistently deep sodium absorption, namely V1331 Cygni (= Lk Hα−120; Cohen and Kuhi 1979), associated with an arc nebula. According to Cohen (1974), arcuate cometary nebulae are bipolar systems viewed with their equatorial disks face-on. In such a situation, their central stars would be seen directly through the material of one entire nebular lobe, consistent with substantial absorption by ejected stellar matter.

At 350 pc, P13S has the following luminosity: 0.04 $L_\odot$ from the nebula between 0.4 and 0.85 μm; 13 $L_\odot$ between 1 and 19 μm, 15 $L_\odot$ between 19 and 160 μm, and more than 4 $L_\odot$ beyond 160 μm (cf. Cohen 1973, Appendix A) from the infrared source. The bolometric luminosity, therefore, is at least 32 $L_\odot$. Such a luminosity could be indicative of a T Tauri star, or of a low-mass star (around 1 $M_\odot$) that has evolved substantially from the main sequence (e.g., see Iben 1967). If the circumstellar TiO shell had been ejected from the photosphere of an evolved star, say an early M giant, this star would by now be high on its post–main-sequence convective track, continuing to lose mass and evolving eventually into a planetary nebula. However, its location within a dark cloud would then be most unusual. Equally, to explain the absence of Hα emission from the zone wherein the forbidden lines arise, one would have to appeal to a region in which all the hydrogen was in molecular form. If the evolution of this M giant had progressed far enough, one would expect the outer hydrogen envelope to have been expelled; in that case, the forbidden-line region, whether shocked or not, would have to represent material lost subsequent to the ejection of the hydrogen-rich layers.

We prefer the alternative, that P13S is a very young T Tauri star, high on its convective track, which has recently expelled its outer TiO–rich layers. Again, the absence of hydrogen emission even in the nebular reflection of the embedded stellar spectrum is rather puzzling, although it is possible that the hydrogen-emitting zone is highly obscured as seen from the nebula (see Cohen [1982] for a discussion of anisotropic T Tauri spectra). At least the presence of another T Tauri star, P13N, in Lynds 1473 means that it is legitimate to call upon recent star formation in this cloud.

Some problems are common to both interpretations, namely the absence of hydrogen emission; understanding the structure and location of the forbidden-line region. P13S would be an excellent candidate for nebular spectropolarimetry which could elucidate the relative locations of the emission line zones, the TiO absorbers, and the reflected continuum. Particularly intriguing is the information on the material apparently recently ejected from the photosphere of the embedded star. Either we are witnessing the expulsion of the photosphere of an M giant, heralding the formation of a planetary shell, or we are seeing the turmoil that characterizes the earliest phases of star formation, when polar flows from T Tauri stars interact with primordial disklike structures and mass loss rates are extremely high, albeit for very short periods. Perhaps the T Tauri hypothesis is somewhat more plausible, given the existence of Lynds 1473, yet significant problems remain in the detailed interpretations of both optical and infrared spectra of P13S.

V. CONCLUSIONS

We find evidence for low-mass star formation in Lynds 1473, represented by P13N, an M2.5 T Tauri star.

P13S is a cometary nebula whose embedded star lies at the apex of the parabolic nebulosity, suffers considerable extinction ($A_V \approx 40$ mag) not shared by P13N and presumably arising in an equatorial disklike structure, and has a bolometric luminosity of at least 32 $L_\odot$. This embedded star has, or recently had, a cool photosphere which has been expelled in the direction of the parabolic nebula. It is unclear whether it is an extremely young T Tauri star, or an evolved low-mass star, now an M giant, although the latter hypothesis seems less likely and would have resulted in considerable damage to the ice grains in the molecular cloud.

M. C. thanks the staffs of the UKIRT and of KPNO for their assistance with the broad-band photometry, particularly D. H. Beattie and T. Lee; P. Harvey for the opportunity to use his far-infrared photometer on P13 during a collaborative flight on the KAO and B. Wilking for his help in obtaining the airborne data; L. V. Kuhi for sharing time on the Lick 3 m telescope to acquire the optical spectra; G. Baran and J. Bally for supplying unpublished CO data on Lynds 1473; C. McKee, L. V. Kuhi, and J. G. Phillips for valuable discussion. P. M. W. thanks Charles Cunningham for assistance with the 3 μm spectrometry.

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