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MULTIFREQUENCY OBSERVATIONS OF THE COMETARY NEBULA P18 (NGC 2316)[1]

J.A. López[2], M. Roth[2,3,4], S.D. Friedman[3], and L.F. Rodríguez[2,5]

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RESUMEN

Se han obtenido observaciones a distintas frecuencias para la nebulosa cometaria P18 (NGC 2316). El conjunto de datos consiste de imágenes CCD en las bandas *R* e *I*; fotometría infrarroja en las bandas *J,H,K* y *L'* y mapas en las bandas *H* y *K*, así como observaciones en radio continuo a λ 6-cm. Esta información ha sido combinada con fotometría previamente publicada a 10 y 22 μm y datos de los observatorios espaciales IRAS y Kuiper. Los resultados indican que P18 es una región H II compacta localizada a una distancia de ∿ 1 kpc la cual está siendo excitada por una estrella temprana tipo B inmersa en la nube y cuya luminosidad es $L = 1.4 \times 10^3$ $L_\odot$. Dos condensaciones localizadas cerca del ápex de la nebulosa, evidentes en los mapas óptico-rojo e infrarrojo y que han sido referidas anteriormente como "estrellas" parecen estar más bien relacionadas a luz de la región H II la cual brilla a través de secciones abiertas de la envolvente de polvo circunestelar.

ABSTRACT

Multifrequency observations have been obtained for the cometary nebula P18 (NGC 2316). The set of data consists of CCD frames in the *I* and *R* bands; *J,H,K* and *L'* near-infrared photometry and maps in the *H* and *K* bands, and radio continuum observations at λ 6-cm. These have been combined with previously published photometry at 10 and 22 μm, IRAS and Kuiper data. The results indicate that P18 is a compact H II region located at a distance of ∿ 1 kpc and is being excited by an embedded single early B-type star with $L = 1.4 \times 10^3$ $L_\odot$. Two condensations located near the apex of the nebula, apparent in the optical-red and near-infrared maps and previously misidentified as "stars", are related to light from the H II region shining through the disrupted circumstellar dust shell.

Key words: **STAR FORMATION – NEBULAE-INDIVIDUAL – INFRARED-SOURCES**

I. INTRODUCTION

P18 (NGC 2316) is a nebulous object, first listed by Parsamian (1965) together with other objects under the generic name of "cometary nebulae". These fan-shaped nebulosities have been associated with a variety of underlying objects, ranging from T-Tauri type stars to compact H II regions. Many of these cometary nebulae are found to be reflection nebulosities.

P18 has been studied by Méndez and Parsamian (1974) who obtained low resolution spectra of a blue, featureless continuum. They report the presence of two "stars" near the apex with spectra similar to the nebular one; both had been steadily brightening over a time interval of 12 years. Cohen (1974) also noted these two "stars" and reported near infrared (up to 22 μm) observations for the northeastern one, pointing out its steeply rising energy distribution. IRAS detected a bright point source with an error box which includes P18. An infrared spectrum of the source is found also in the Atlas of Low Resolution Spectra (Olnon and Raimond 1986). Far-infrared observations (40 – 160 μm) obtained from the Kuiper Airborne Observatory have been published by Evans, Levreault, and Harvey (1986). In addition, Cohen *et al.* (1986) have also shown from airborne measurements the presence in P18 of strong unidentified emission bands between 5 and 8 μm. Sellgren (1986) studied P18 in molecular hydrogen emission and found that it contains several H_2 lines whose intensity ratios agree with predictions of excitation due to *UV*-pumped fluorescense. P18 is also included in the survey of molecular material associated with galactic H II regions by Blitz, Fich, and Stark (1982) who list an antenna temperature $T_A = 15$ K and velocity dispersion $\Delta v = 2.5$ km s^{-1} which suggests moderate activity in the region. The near kinematical distance inferred from the radio data ($V_{CO} = 13.4 \pm .4$ km s^{-1}) is 940 pc.

In this paper, multifrequency observations of P18 are presented and analyzed focusing attention on the nature of the underlying object. The observations are presented in §II, results and discussion are presented in §III and conclusions are given in §IV.

1. Based partially on observations collected at the Observatorio Astronómico Nacional of San Pedro Mártir, B.C. México.
2. Instituto de Astronomía, Universidad Nacional Autónoma de México.
3. Center for Astrophysics and Space Sciences, UCSD.
4. Visiting astronomer, Cerro Tololo Inter-American Observatory, operated by AURA under contract to the NSF.
5. Harvard-Smithsonian Center for Astrophysics.

II. OBSERVATIONS

a) *CCD Observations*

R and *I* band CCD images were obtained on the night of 5 April 1987 at the UCSD/UM 1.5-m telescope at Mount Lemmon, Arizona. The CCD used is a GEC optimized for use in the red, and is described in detail elsewhere (Friedman, Jones, and Puetter 1986). The spectral bandpasses used were selected to be approximately the same as normal *R* and *I* photometric bandpasses (Johnson 1965). However, the spectral intervals were slightly different, as follows: *R* (6000 – 7000 A) and *I* (7100 – 10600 A), where the wavelength limits specify the full width at half-maximum transmission. The photometric data were reduced using standard techniques, including flat-fielding and flux calibration. The reductions were performed using VISTA, an interactive two-dimensional software package run on a VAX-11/780 computer.

The Mount Lemmon CCD pixel size is 22 μm, which at a scale of 9 arcsec/mm on the 1.5-m telescope and with a focal reducing lens, implies that each pixel views 0.5 arcsec on the sky. Allowing for seeing degradation, the image quality shown exhibits an angular resolution of approximately 2.5 arcsec or better. Photometric calibration of the CCD images was achieved by comparison with the standard stars SA 101-324 and SA 105-205 (Landolt 1973; Kunkel and Rydgren 1979).

R and *I* band CCD contour plots are shown in Figures 1*a* and 1*b*. Adjacent contour levels have a ratio of 1.585; that is, there are five levels per decade of surface brightness. The highest contour corresponds to 1.92 X 10^{-8} and 5.62 X 10^{-9} watts cm^{-2} μm^{-1} ster^{-1} at *R* and *I*, respectively. The faintest level corresponds to 1% of these values. The total flux in each band in 10 arcsec diameter apertures centered at each of the major bright spots, northeast (NE) and southwest (SW), is given in Table 1.

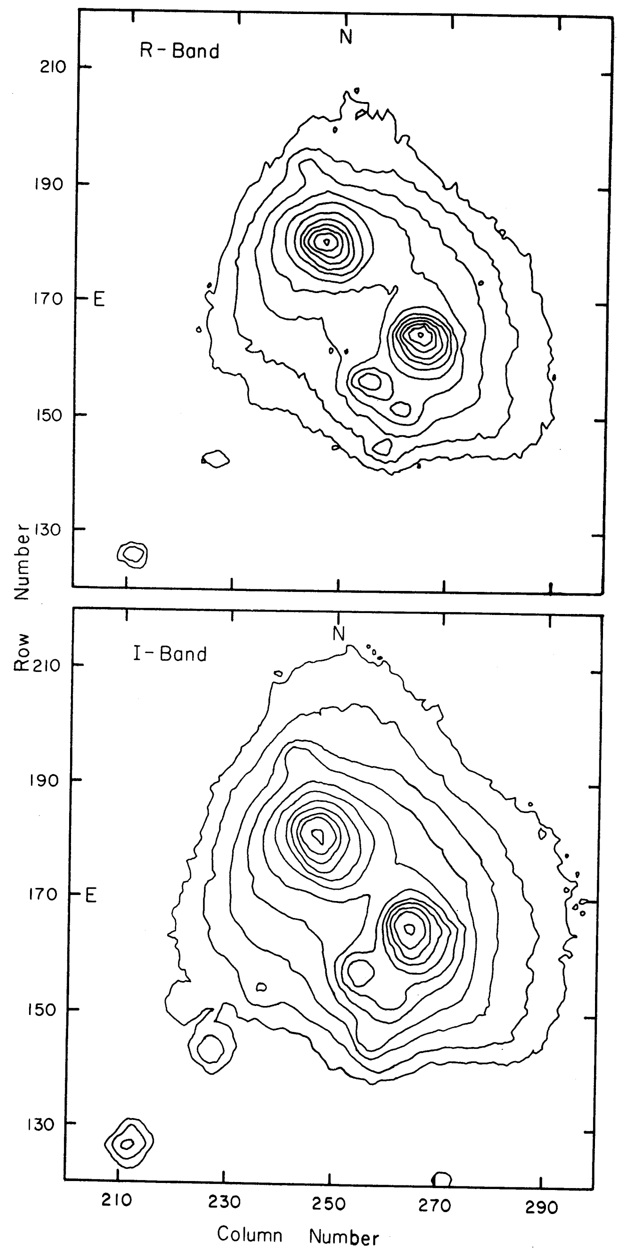

Fig. 1. CCD contour map of P18 at *R*-band (*a*) and *I*-band (*b*). The ratio of adjacent contours is 1.585. Highest contours correspond to 1.93 X 10^{-8} and 5.62 X 10^{-9} watts cm^{-2} μm^{-1} ster^{-1} at *R* and *I*, respectively. Pixel size is 0.5 arcsec. The double structure of the source also apparent in Figures 2, 3 and 5 is discussed in the text.

TABLE 1

PHOTOMETRY OF P18

Band	log Sν (Jy)	Notes
R	{−1.51	NE knot
	{−1.56	SW
I	{−1.26	NE
	{−1.30	SW
J	−0.88	NE
H	{−0.75	NE
	{−0.73	SW
K	{−0.71	NE
	{−0.70	SW
L'	−0.80	NE
[10][a] μm	0.52	NE
[22][a]	1.76	NE
[12][c]	1.30	...
[25][c]	2.17	...
[40][b]	2.49	...
[50][b]	2.61	...
[60][c]	2.61	...
[100][b]	2.55	...
[100][c]	2.75	...
[160][b]	2.41	...
6 cm	−2.42	...

a. From Cohen 1974; b) from Evans *et al.* 1986; c) IRAS.

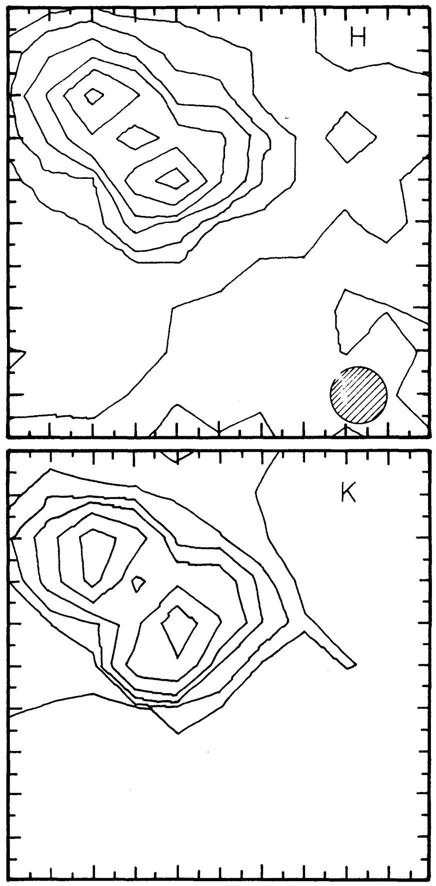

Fig. 2. Infrared *H* and *K* maps of P18 obtained with a 7 arcsec diaphragm (hatched circle) on positions separated by 5 arcsec.

b) *Near Infrared Observations*

Near infrared low resolution maps in the *H* and *K* bands and near infrared photometry (*J,H,K* and *L'*) were obtained on the nights of 1986 November 19 and 20 on the 2.12-m telescope of the Observatorio Astronómico Nacional at San Pedro Mártir, Baja California, México, using the equipment described by Roth *et al.* (1984). The maps were obtained by performing 5 second integrations through a 7″ diaphragm on positions separated by 5″. Sky subtraction was obtained by the standard procedure, with a beam separation of 90″. The photometry, performed in a similar manner, was compared against a set of standard stars in the San Pedro Mártir photometric system described by Tapia, Neri, and Roth (1986). The *H* and *K* maps are shown in Figures 2*a* and 2*b*. The photometric results are presented in Table 1.

Uncalibrated images in *H* and *K* bands were also obtained with the 1.5-m telescope of CTIO with the recently available infrared imager on the night of November 16, 1987. Both, *H* and *K* images are virtually identical. Excess noise was present in the array due to a ground loop. For this reason no attempt was made to calibrate the images. The contour plot shown in Figure 3 shows the result from the average of 5 X 60 second integrations "on object" and 5 X 60 sky integrations subtracted through the *K* filter. The image has 62 columns by 58 rows with a plate scale of 0.92″/pixel. The two peaks are heavily saturated.

c) *IRAS Data Analysis*

As mentioned above, P18 is an entry in the IRAS Point Source Catalog. ADSCAN and SCAMPI algorithms were requested from IPAC and the spatial distribution of the far infrared flux and the fluxes themselves were reanalyzed. The IRAS synthetic bands of Cohen and Schwartz (1987) were used for the latter. The correlations obtained from the ADSCAN tracings with a point source algorithm for the four IRAS bands were in all cases better than 98%. Although the angular resolution of the IRAS detectors is insufficient to resolve details at a scale of ∿ 15″, which is roughly the separation between the peaks of the two bright condensations, the extended flux in the visible and near-infrared extends over a linear distance of ∿ 30″, which is approximately the resolution in declination of the 12 and 25 μm IRAS bands. The scans of the ADSCAN algorithm were obtained from almost North-South passes (P.A. 9.5°) of the satellite and the fit to a single point source is practically perfect, with a point-source template correlation of 0.999 at 25 μm. The IRAS far infrared fluxes are included in Table 1.

P18 is also included in the IRAS Atlas of Low Reso-

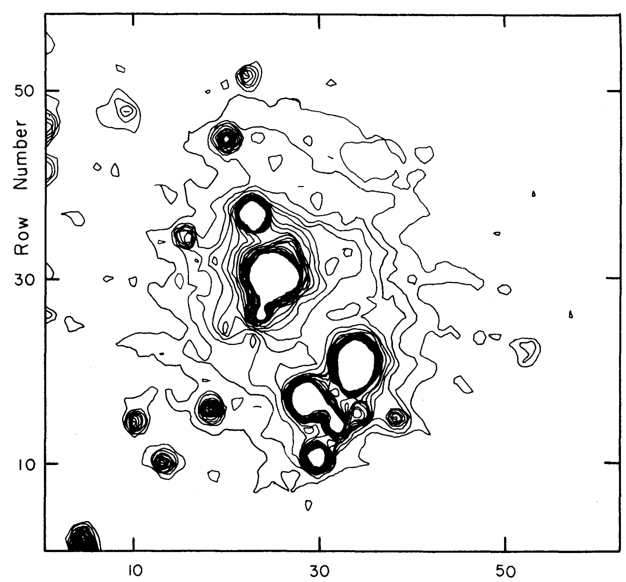

Fig. 3. *K* band contour map of P18 obtained with the Infrared Imager of CTIO. The scale is 0.92 arcsec/pixel.

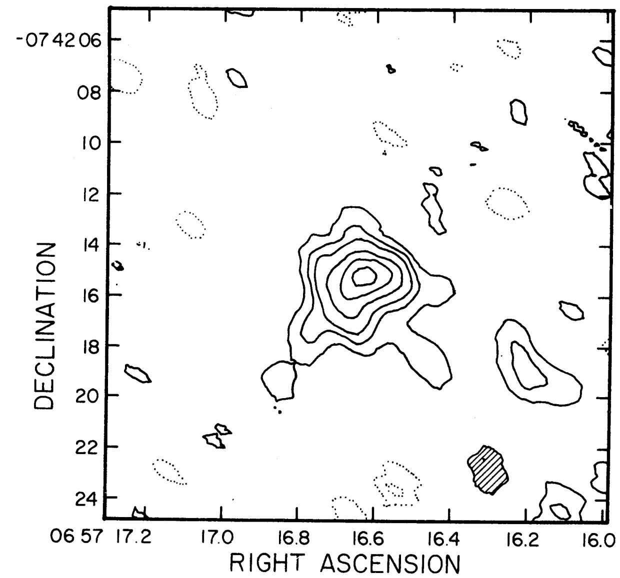

Fig. 4. *VLA* map of the P18 compact H II region. Contours are −0.3, −0.2, −0.1, 0.1, 0.2, 0.3, 0.5, 0.7 and 0.9 of the peak flux per synthesized beam, 1.2 mJy/beam. The shape of the beam (hatched) is due to the A/B configuration.

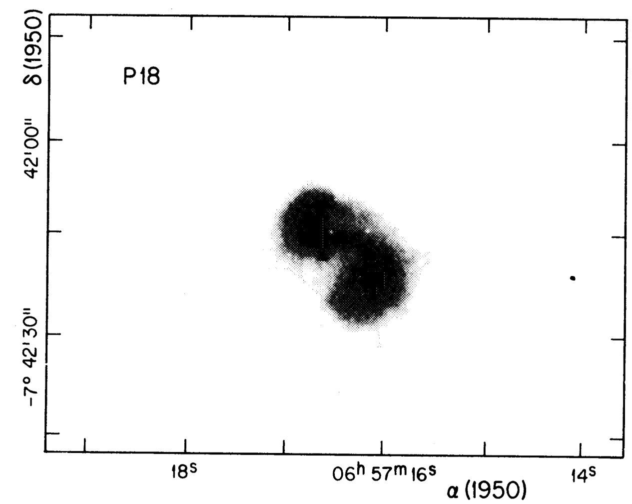

Fig. 5. An enlargement of the P18 region reproduced from the SRC Short Red Atlas. The position and extent of the radio source is indicated by the cross.

lution Spectra (Olnon and Raimond 1986). Its spectrum shows definite characteristics of a compact H II region with a very red continuum and the presence of the 11.3 μm emission "line", though no atomic lines are apparent.

d) *Radio Observations*

Continuum observations at 6-cm of the P18 region were made during 1987 November 11, with the Very Large Array of the National Radio Astronomy Observatory[6]. The *VLA* was then in the A/B configuration, providing an angular resolution of 1″ for a southern region. The observations were made with an effective bandwidth of 100 MHz during approximately 20 minutes. 0727-115 was used as a phase calibrator and 3C286 as absolute amplitude calibrator. A single source with total flux of 3.8 mJy was detected and a cleaned map made with uniform weighting is shown in Figure 4. The peak flux of the map is 1.2 mJy/beam and the peak position is at $\alpha(1950) = 06^h57^m16^s.63 \pm 0^s.01$; $\delta(1950) = 07°42' \; 15.2 \pm 0.1$. No other sources were detected within ∿ 2′ of the center of the map. The radio source coincides with IRAS 06572–0742, which has $\alpha(1950) = 06^h57^m16^s.8$; $\delta(1950) = 07° \; 42'16''$ and an error ellipsoid of 29″ X 8″ with P.A. = 99°. The radio source is clearly resolved, with a half power angular dimension of ∿ 2″.

The position of the radio source with respect to the condensations is indicated in Figure 5 which is an enlargement of the region reproduced from the SRC Short Red Atlas.

III. RESULTS AND DISCUSSION

The energy distribution of P18 is shown in Figure 6. Clearly, the total radiation has a bimodal distribution, indicating a different nature at short and long wavelengths. At near-IR wavelengths the flux shows quite a flat distribution, whereas the flux at wavelengths longer than 5 μm rises steeply and peaks at ∿ 100 μm becoming the dominant contributor to the total luminosity in this object. The photometric values at 10 and 22 μm in this figure are taken from Cohen (1974); the overlap between these data and the IRAS fluxes is clear. In addition, flux values at 160, 100, 50 and 40 μm from the Kuiper observations by Evans *et al.* (1986) are also shown.

The source appears double at visual and near infrared wavelengths (see Figures 2, 3 and 5). There can be little doubt that these two condensations correspond to both "stars" mentioned by Méndez and Parsamian (1974) and Cohen (1974). A near infrared colour-colour diagram of P18 locates the double source within the locus of the optically thin H II regions (Tapia 1981; Allen 1984). Notice in Table 1 that the colours for both sources are practically identical.

The photometric similarity of both condensations, their puzzling simultaneous brightening reported by Méndez and Parsamian (1974), the fact that their near infrared colours do not correspond to reddened stars, and the single source detection of the IRAS and radio results lead to the conclusion that these condensations are rather related to the emerging radiation from an inner compact H II region shining through "holes" of a disrupted circumstellar dust shell. In other words, the condensations are the visible part of an embedded H II region that

6. NRAO is operated by Associated Universities, Inc., under contract with the National Science Foundation.

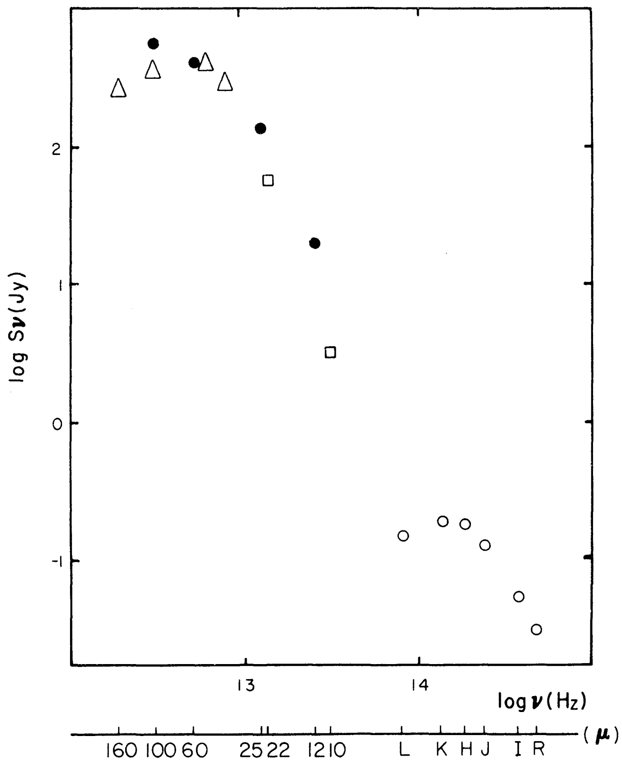

Fig. 6. Energy distribution of P18. Open circles this paper, filled IRAS data, squares from Cohen (1974), triangles from Evans *et al.* (1986).

is beginning to emerge from the cloud. This situation is similar to the one described by Tapia *et al.* (1985) for the cometary nebula GM24.

Assuming that the IRAS far-infrared is due to re-emission by dust heated by one central source, the calculated luminosity is $L \cong 1.36 \times 10^3\ L_\odot$ corresponding to a B2 – B3 type star located at a distance of ∿ 1 kpc. The IRAS colour temperatures are $T_{(12-25)} = 149$ K, $T_{(25-60)} = 95$ K and $T_{(60-100)} = 55$ K respectively, indicating a distribution of temperatures within the extended heated dust environment.

Likewise, assuming the radio source to be an optically thin H II region at ∿ 1 kpc and with an electron temperature of 10^4 K, its energy requirement is estimated to be an ionizing photon flux of $3.4 \times 10^{43}\ s^{-1}$. This flux corresponds again to a ∿ B3 ZAMS star (Thompson 1984) in good agreement with the result obtained above from the IRAS data.

IV. CONCLUSIONS

In summary, the cometary nebula Parsamian 18 is a region where star formation has occurred recently. The radio source detected reveals a compact H II region ionized by an early B-type star which is heavily obscured by a dust shroud. This star is responsible for the far infrared flux and the optical and near-infrared condensations. These condensations are visible parts of the embedded H II region that is beginning to emerge out of what seems a rather patchy circumstellar medium. The confirmation of the presence of an early B-type star in P18 is important since such an object is required to account for the *UV*-pumped fluorescence observed in the H_2 lines by Sellgren (1986).

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S.D. Friedman: Center for Astrophysics and Space Sciences, UCSD, C-011 La Jolla, Ca. 92093, USA.
J.A. López and M. Roth: Instituto de Astronomía, UNAM, Apartado Postal 877, 22830 Ensenada, B.C., México.
L.F. Rodríguez: Instituto de Astronomía, UNAM, Apartado Postal 70-264, 04510 México, D.F., México.