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The UV (IUE) spectrum of the planetary nebula PC 11 (HD 149427)*

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Abstract. The UV spectrum of PC 11 is found to show variations in the strength of the O III] 1666Å , N III] 1750Å and C III] 1909Å emission lines. The detection of continuum emission in the wavelength interval 2650Å to 3200Å indicates that the central star of PC 11 has an early F-type dwarf companion. The very low level of UV continuum in the wavelength interval 1150Å to 1900Å and the non-detection of the central star in the UV images recently taken with HST suggest that the hot whitedwarf or sub-dwarf like central star may be obscured by a dusty disk. The variations in the UV emission lines observed during the period 1987 to 1994 may be the consequence of variable emission coming from high-velocity jet-like emission visible in optical images also taken with HST in the light of [O III]. Based on our UV observations, we confirm our identification of PC 11 as a planetary nebula with a close binary central star. Adopting the absolute magnitude of a F0V companion yields a distance of 485 pc to PC 11. If we assume a typical expansion velocity of 12.5 km s^{-1} and considering the observed angular diameter of the nebula (4.1″), we find the age of PC 11 to be 376 years. The AGB phase of evolution of the central star seems to have been terminated only recently.

Key words: ISM: planetary nebulae: individual: – ultraviolet: stars – stars: binaries: close – stars: evolution – stars: emission-line, Be – stars: AGB and post-AGB

1. Introduction

PC 11 (HD 149427 = IRAS 16336-5536 = PN G 331.1-05.7) is a peculiar object, classified as a planetary nebula (PN, hereafter) (Acker et al. 1992) but also as a D'-type symbiotic star (Allen 1982). The most recent analysis of the optical spectrum of PC 11 by Gutiérrez-Moreno & Moreno (1998, hereafter GMM98) concludes that it is a young low luminosity compact and dense PN with a central star having an energy balance temperature of 105,000 K. The classification of PC 11 as a PN and not as a symbiotic star is based on the low excitation observed in the optical spectrum and its location in the HR diagram.

From a preliminary analysis of the IUE UV spectra of PC 11 Parthasarathy et al. (1993) found variations in the strength of O III] and N III] lines. They also suggested that PC 11 is a PN and that the central star is a binary with a A-F type companion.

Discovering and studying binary central stars in PNe is important to understand the common-envelope evolutionary phase and also to get distance esimates to PNe. Binary central stars are relatively rare in PNe. There are about 15 close-binary central stars known (Bond & Livio 1990; Livio 1997). Some of them are among the hottest known central stars.

Milne & Aller (1982) made radio observations of PC 11 at 14.7 GHz and found a flux density of 41 mJy. Kenny et al. (1992) measured a flux density of 26 mJy at 5 GHz. The far-IR (IRAS) colours are similar to those usually observed in PNe (Parthasarathy & Bhatt 1989). We have obtained UV (IUE) spectra of PC 11 on six occasions and an analysis of these spectra is presented in this paper.

2. Observations

Low resolution ultraviolet (1150Å to 3200Å) spectra of PC 11 were obtained with the SWP and LWP cameras onboard the IUE satellite using the large entrance aperture (10″ × 23″). The angular diameter of PC 11, as revealed by HST images available in the Data Archive taken through several narrow filters is ∼4″. Hence, the entire nebula and the central star must have always been observed well centred within the large aperture of the IUE cameras. In fact, during the 1987, 1988 and 1989 observations the optical detector on board IUE (FES) was able to detect this 12.7 mag star, allowing a direct and hence accurate target acquisition into the science aperture. On the other hand, during the 1992 and 1994 observations, the centering of PC 11 into the large apertures was ensured by the Blind Offset technique, checking the relative guide position (found within 0.8″) with respect to the nominal target coordinates. Observations

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* Based on observations obtained with the International Ultraviolet Explorer, retrieved from the IUE Final Archive at VILSPA and on observations made with the NASA/ESA Hubble Space Telescope, obtained from the data Archive at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555

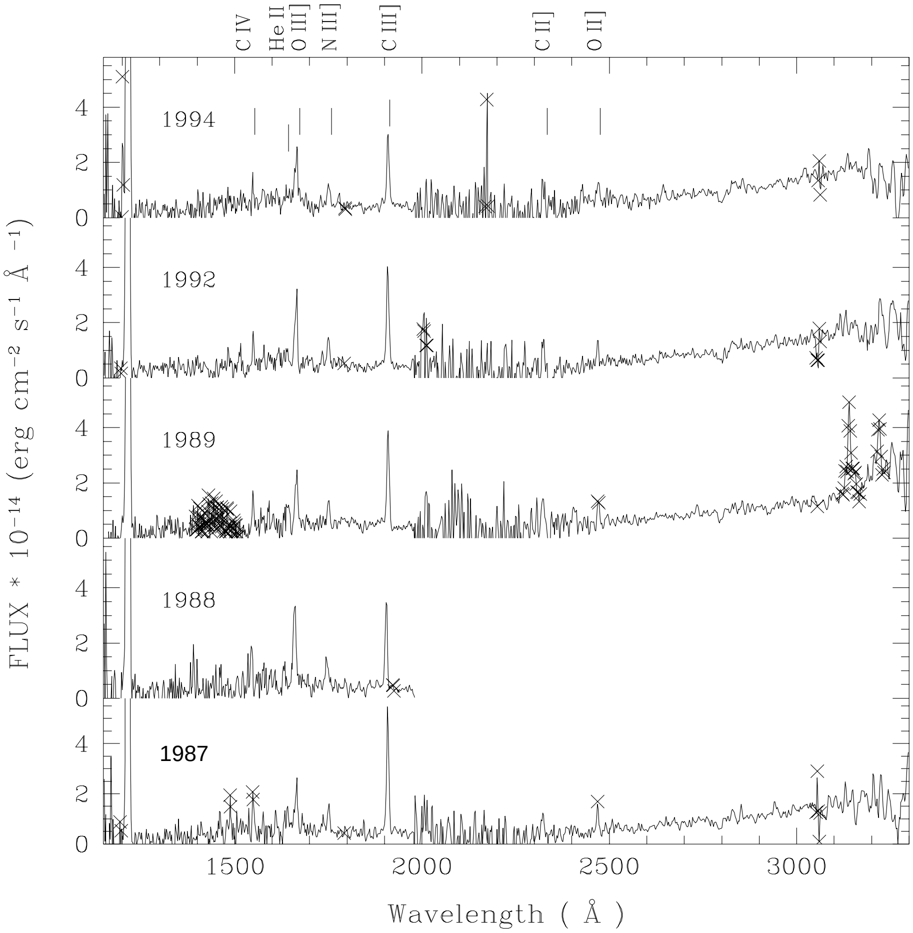

Fig. 1. The spectral evolution of PC 11 during seven years. From bottom to top, the merged SWP and LWP spectra since 1987 are shown. Spurious features are marked with crosses.

Table 1. Journal of IUE observations.

Date	Image	Exposure time	Image	Exposure time
Sep.10, 1987	SWP31820	5400 s	LWP11590	3600 s
Sep.12, 1987	SWP31829	7200 s		
Jul.19, 1988	SWP33940	5940 s		
Mar.26, 1989	SWP35859	7200 s	LWP15252	4800 s
Apr.23, 1992	SWP44460	7200 s	LWP22875	3600 s
Apr.23, 1994	SWP50612	9000 s	LWP27973	5100 s

were made on six occasions during the period 1987 to 1994 as reported in Table 1.

All spectra have been re-extracted from the IUE Final Archive at VILSPA which were re-processed using the IUE NEWSIPS pipeline which applies the SWET extraction method as well as the latest flux calibration and close-out camera sensitivity corrections (Garhart et al. 1997). Line-by-line images have been inspected for spurious features. In this work only the image SWP31829 has been used to represent the far-UV spectrum in 1987 since it is best exposed and since the noisy image SWP31820 shows presence of cosmics features at positions of the registered spectrum especially in the region at 1300Å and 1700Å. For the other exposures contaminated pixels on the registered spectrum have been identified (see also Fig. 1).

3. Analysis

Spectra of PC 11 from 1150Å to 3200Å in absolute flux units acquired in several epochs from 1987 to 1994 are shown in Fig. 1, where the spectral evolution is apparent.

3.1. Emission lines

The prominent emission lines in the UV spectrum of PC 11 correspond to O III] at 1666Å, N III] at 1750Å and C III] at 1909Å. Weaker emission features are also identified as C IV at 1550Å and He II at 1640Å in the short wavelength range and as C II] at 2325Å and O II] at 2470Å in the long wavelength range, the latter despite of a few bad pixels identified in two line-by-line images. Upper limits of 3-4Å on the equivalent widths of C IV, C II], and O II] lines can be given.

From the inspection of Fig. 1 it is clear that there are variations in the strength of the UV emission lines in the spectrum of PC 11. Particularly, the variations in line strength of C III] 1909Å and O III] 1666Å are significant (Table 2). In addition, the Mg II 2800Å absorption line shows a variable and asymmetric profile and appears to be affected by emission in the 1992 and 1994 spectra. There is a wavelength shift by $\sim$ -4.4Å of the emission lines in the 1988 SWP33940 spectrum, which would correspond to a velocity of $\sim$-880 km s^{-1}. A wavelength shift could have been produced by a de–centering of the target along

Table 2. Equivalent widths and fluxes of main emission lines in the UV spectrum of PC 11

	O III] 1666 Å		N III] 1750Å		C III] 1909Å	
Epoch	W_λ (Å)	Flux[1]	W_λ (Å)	Flux[1]	W_λ (Å)	Flux[1]
1987	16 ± 3	1.3 ± 0.1	9 ± 1	0.60 ± 0.08	60 ± 10	3.6± 0.2
1988	30 ± 4	2.3 ± 0.1	9 ±1	0.68 ± 0.09	48 ± 5	2.9 ± 0.1
1989	30 ± 3	2.0 ± 0.1	13 ± 1	0.81 ± 0.03	60 ± 8	2.7 ± 0.1
1992	40 ± 7	2.4 ± 0.2	13 ± 2	0.92 ± 0.06	40 ± 5	3.0 ± 0.1
1994	22 ±2	1.7 ± 0.1	11 ± 4	0.56 ± 0.07	38 ± 8	2.2 ± 0.1

[1] Flux in units of 10^{-13} erg cm^{-2} s^{-1}

the minor axis of the oval science SWLA aperture. Such shift would correspond to a ∼4″offset and hence it would have been at the border with very likely loss of flux. This cannot be accounted by the observed flux (the continuum has not changed with respect to other exposures at other epochs) and primarily by the fact that the standard automatic IUE acquisition procedure called ACQ, with an accuracy better than 1″, was used for this exposure. This might suggest an outflow variability.

The strength of the brightest emission lines detected at various epochs are given in Table 2. The measures have been performed interactively since gaussian fits could not satisfactory reproduce the observed profile. Averaged values over several measures are reported and errors are standard deviations from the mean. The UV spectrum of PC 11 does not show any evidence that it is a symbiotic star. Feibelman & Aller (1987) used the flux ratio of C III] 1909Å / Si III 1892Å as a discriminant for distinguishing PNe from symbiotic stars and related objects. In symbiotic stars the Si III line at 1892Å is often strong. The Si III emission line at 1892Å in the spectrum of PC 11 is very weak or absent. The flux ratio C III] 1909Å / Si III 1892Å is very similar to that observed in 80% of the PNe which confirms that PC 11 is a PN and not a symbiotic star. The recent optical nebular spectrum of PC 11 and its analysis also shows that PC 11 is a PN (GMM98). GMM98 estimate an electron density of log (N_e/cm^{-3}) = 5.2 ± 0.2 and an electron temperature T_e = 18400 ± 300 K, typical of high density PNe. Variations in the [O III] lines in the optical also appear to be evident if they are compared with previous results obtained by Webster (1966) and by Acker et al. (1989).

Parthasarathy et al. (1993) suggested that PC 11 may have a binary central star based on the UV emission line variability and on the stellar continuum detected in the IUE spectrum. PC 11 may be similar to the PN K1−2 which has a close binary central star (Bond & Livio 1990). The variations in the UV emission lines in PC 11 may be related to the presence of jets and/or knots in the nebula surrounding the binary nucleus, like those observed in K1−2 (Bond & Livio 1990).

HST archive images of PC 11, recently obtained as part of a proposal by Bode (data unpublished), were inspected in order to investigate possible connections between the nebular morphology and the spectral variations observed (see Fig. 2).

The HST data consist of several images taken with the Wide Field Planetary Camera 2 (WFPC2) onboard HST on 1999 July 24 through the UV wide F218W filter (not shown) and the optical narrow F507N and F656N filters (centred at the wavelengths corresponding to the emission lines of [O III] and Hα).

While nothing was detected at UV wavelengths at the position of PC 11 through the F218W filter (nor even the hot central star), the high resolution (0.045″/pixel) images taken through the F507N and F656N narrow filters revealed a nebular morphology consisting of a bright and elongated central condensation of quasi-stellar appearance (diameter ≤ 0.8″), where most of the emission is concentrated, surrounded by a much fainter round-shaped nebulosity with a total extension of ∼ 4.1″. The angular diameter (10″) of PC 11 estimated by Moreno et al. (1991) from very low resolution photographic images seems to be wrong.

The extended nebulosity surrounding the central core looks quite homogeneous in the light of Hα. However, a clear jet-like emission and an apparently associated counter-jet are visible in [O III]. The brightest jet emission is observed coming from a bright knot located at a distance of 2.1″to the north-west of the nebula at a position angle which is almost coincident with the major axis of the elongated core.

This jet-like structure might be the origin of the high velocity features (up to 120 km s^{-1}) and faint double peak emission detected by GMM98 in the spectrum of what they called the '[O III] extension' of PC11. Several other faint condensations lying at other position angles are tentatively detected, but this must be confirmed with deeper exposures of the same field with HST.

3.2. UV Continuum

The UV continuum in the wavelength interval 1150Å to 1900Å is very weak or absent, consistent with the non-detection of the central star by HST. However, in the LWP spectra a rising stellar continuum from 2650Å to 3200Å is clearly present (Fig. 1). Despite the low quality of the spectra in the 2200Å region, an extinction of E(B-V)=0.4±0.2 is found, in reasonable agreement with the optical estimate of E(B−V) = 0.47 given by GMM98.

We compared the LWP spectra of PC 11 with the spectra of stars in the IUE UV spectral atlas by Heck et al. (1984) and find that it closely resembles that of an early F-type star. In Fig. 3, the average of the LWP spectra dereddened for E(B−V) = 0.47 is shown together with the unreddened spectra of the standard star HD 59846 of spectral type F0 V (dotted line). The continuum in

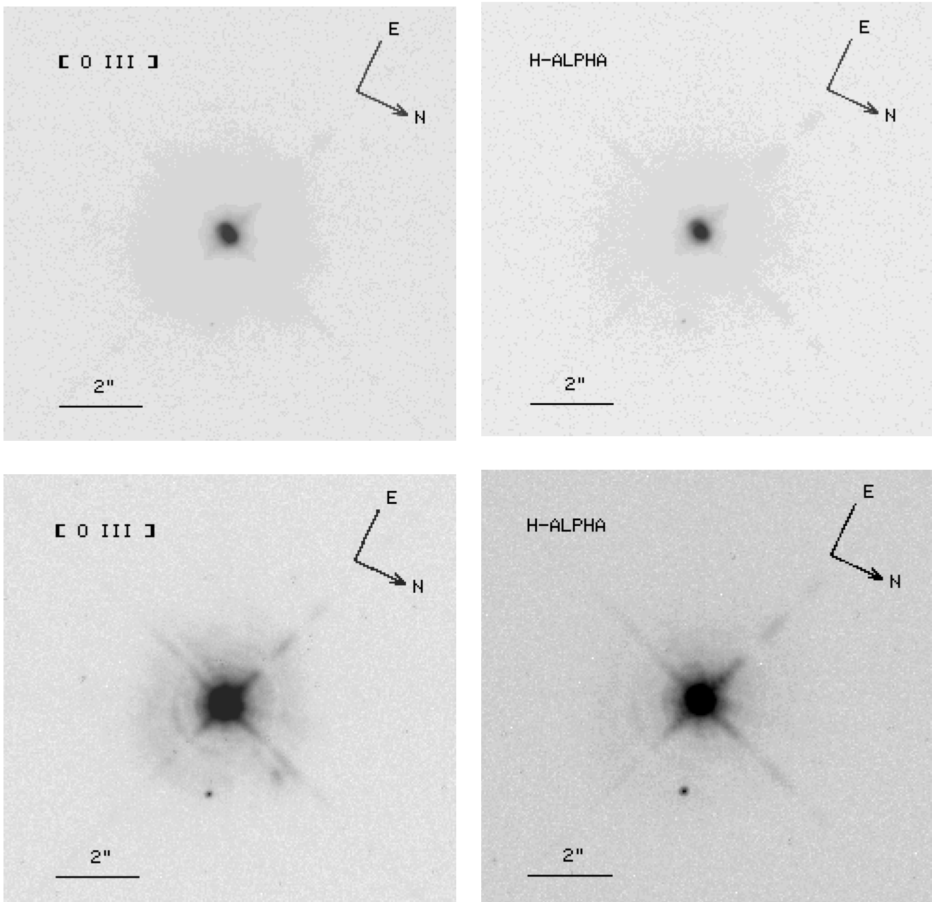

Fig. 2. Logarithmic scale images of PC 11 extracted from the HST Data Archive. They correspond to WFPC2 exposures taken in the light of [O III] (left) and Hα (right) shown with two different contrast levels. Note the elongated core (upper panel) and the presence of jet-like emission in [O III] and not in Hα (bottom panel).

the wavelength interval 2650 to 3200Å fits very well with that of an F0 V star. From this result we can conclude that, despite the difference in depth of the Mg II 2800Å absorption line, which can be partially due to interstellar contribution and/or intrinsic emission of the source, the central star of PC 11 must be a binary with an early-F type companion star. A similar conclusion was reached by GMM98 from their optical observations. They compared the optical continuum with stellar atmospheric models and derived an effective temperature of 7,500 K and log g = 4.5 (cgs) for the companion star.

Since we are speaking of a companion having an early-F spectral type, this has a direct consequence on the distance. Previous distance estimates to PC 11 range from 3 to 8.56 kpc (see Acker et al. 1992). The presence of a binary companion to the central star can be used to derive a relatively accurate spectroscopic distance. Adopting the absolute magnitude of an F0-F1 V companion GMM98 found that the distance to PC 11 to be close to 420 pc. We have adopted the absolute visual magnitude of the F0V companion to be 2.7 and the visual magnitude to be 12.68. After taking into account the interstellar extinction we find the distance to PC 11 to be 485 pc, which is in agreement with the estimate made by GMM98. If we assume a typical expansion velocity of 12.5 km s^{-1} appropriate for relatively small nebulae like PC 11 we find its age (with an angular diameter of 4.1$''$) to be 376 years. Gussie & Taylor (1994) from an analysis of the expansion velocities of large sample of PNe found two components in the distribution. Nebulae in the low expansion velocity component (12.5 km s^{-1}) to be smaller in linear extent than the high expansion velocity PNe (27.5 km s^{-1}). If we use 27.5 km s^{-1} expansion velocity which appears to be typical for large PNe then the age of PC 11 turns out to be 171 years. In any case it appears that PC 11 is relatively a nearby very young PN with a binary central star. Its AGB phase of evolution appears to have been terminated within the last few hundred years.

GMM98 estimated the energy balance temperature of the central star to be 105,000 K. The UV continuum at the shorter wavelengths is very weak or absent and we can only give an upper limit to the detection of He II 1640Å line in the UV spectrum (equivalent width $\leq$ 2 Å), expected to be strong at such a high temperature. In addition, the He II 4686Å line is not detected in the optical spectrum. The effective temperature of the central star may be lower than the energy balance temperature. A careful analysis of high resolution and high signal to noise ratio optical spectrum of PC 11 using photo-ionization model may yield a correct estimate of the effective temperature of the central star.

Since the absence of a strong UV continuum in the wavelength interval 1150Å to 1900Å cannot be accounted by the interstellar reddening we conclude that it is likely that the hot white-dwarf like central star is obscured by a dusty disk. The continuum flux in the UV and in the optical appears to be mostly contributed by the F dwarf companion. PC 11 appears to be sim-

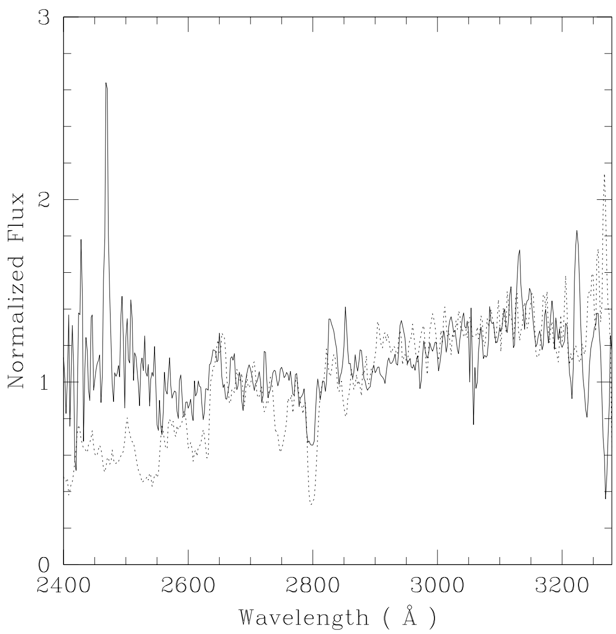

Fig. 3. The average of the LWP spectra (solid line) of PC 11 dereddened with E(B-V)=0.47 (see text) compared with those of HD 58946 (F0 V) (dotted line)
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ilar to the PN Sh2-71 and LoTr5 which have binary central stars with G-type companions (Feibelman 1999; Feibelman & Kaler 1983; Bond & Livio 1990).

4. Discussion and conclusions

The variations in UV emission lines in the spectrum of PC 11 and the F-type stellar continuum in the wavelength range 2650Å to 3200Å suggest that the central star of PC 11 is a close binary system with an early-F dwarf companion. The jet-like structures observed in the light of [O III] could be triggered by episodic physical interactions between the two components of the binary system.

On the other hand, the changes observed in the Mg II 2800Å profile might be originated in the chromosphere of the cooler star, heated by the hot companion. Other explanations, however, cannot be ruled out, like effects produced by eclipse or partial eclipse phenomena or rotating star spots in the cool star.

The F-type spectral type assigned to the companion star indicates that the distance to PC 11 must be of a few hundred parsecs. The age of the nebula turns out to be of only a few hundred years.

The absence of a strong UV continuum in the wavelength region 1150Å to 1900Åindicates that the hot whitedwarf or hot sub-dwarf like central star may be obscured by a dusty disk. GMM98 also discussed the possibility of a dusty disk obscuring the central star.

The variations in the UV emission lines may be due to the formation and evolution of jet-like structures and clumpy knots in the shell surrounding the central star of PC 11, ejected from the binary nucleus and observed in the high resolution images of PC 11 taken with HST WFPC2 in the light of [O III]. These high excitation knots of emission might be similar to those observed in the PN K1−2, which also shows evidence for jet-like structures ejected from its binary nucleus. The formation of these jets might indicate the action of hydromagnetic winds, similarly to what it is observed in bipolar flows associated to protostellar objects. The formation and evolution of jet-like structures and collimated outflows in PNe remains unclear. However it appears that it is directly or indirectly related to the presence of a binary companion (Soker and Livio 1994; Bobrowsky et al. 1998).

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