Mon. Not. R. astr. Soc. (1982) **201**, 21–26

Study of planetary nebula K1–2 and its variable nucleus*

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Received 1981 November 30

Summary. New photographic, photometric and first spectroscopic observations of K1–2 indicate this object to be an old, very high-excitation planetary nebula at the distance of 2.4 kpc. The optical variability of the central star in the range B 16.5–17.7 mag has been confirmed. The nucleus has the following parameters: $L_* = 500$–$1000\,L_\odot$, T_z(He II) = 91 000–79 000 K, $R_* = 0.09$–$0.17\,R_\odot$.

1 Introduction

K1–2 ($253+10°1$, $\alpha_{1950} = 8^h\,55^m.7$, $\delta_{1950} = -28°\,45'$) has been classified as a planetary nebula from its appearance on the Palomar Observatory Sky Survey prints (Kohoutek 1962). Its nucleus was found to be variable on the overlap portion of two survey prints with m_{pg} 15.9 and 17.4 mag respectively (Kohoutek 1964). Liller & Shao (1968) confirmed the variability of this star from a search of the Harvard photographic plate collection and reported m_{pg} from 15.7 to at least 17.4 mag between 1898 and 1952. Recently Bond (1979) has presented his results of the photometry of K1–2 in 1978–79, which showed the nucleus to vary from 16.4 to 17.8 mag (blue mag) with a period most probably 0.6707 day. He suggested pulsation as an explanation for the observed light curve being a one-cycle sinusoid.

In this paper we present new photographic, photometric and the first spectroscopic observations of K1–2 which indicate this object to be a very high-excitation planetary nebula having a hot variable nucleus.

2 Observations

We used the prime focus ($f/3$) of the 3.6-m telescope of the European Southern Observatory (ESO) at La Silla, Chile, in order to take a photograph of K1–2 (Plate 1) showing the following structure.

* Based on observations collected at the European Southern Observatory, Chile.

(a) Main nebular body of 69 x 53 arcsec in diameter, PA 95°, being somewhat brighter in the outer parts compared with the central region.

(b) Fainter peripheral non-homogeneous structure extending to about 110 x ~ 53 arcsec in diameter, PA 90°.

The nucleus is located in the nebular centre.

The spectrum of the nebula was obtained with the ESO 3.6-m telescope and the Boller & Chivens Cassegrain spectrograph + Image Dissector Scanner in 1979 April. (Spectral range 4290–5050 Å, dispersion 39 Å mm^{-1}, diaphragm 4 x 1.8 arcsec.) The nebula was scanned in two positions of the slit, 20 arcsec to the west and 20 arcsec to the east of the nucleus, respectively. The integration time was 20 min.

The spectrum is typical for a high-excitation planetary nebula and shows strong emissions of [O III] λλ 5007, 4959, Hβ and He II λ 4686 in both positions of the slit (Fig. 1). A small difference in the radial velocity was found between the slit positions: $RV_{\mathrm{hel,\,West}}$ = (69.5 ± 4.6) km s^{-1}, $RV_{\mathrm{hel,\,East}}$ = (62.0 ± 7.0) km s^{-1}. This difference does not seem to be significant compared to the given errors and we therefore used the mean value RV_{hel} = (66 ± 4) km s^{-1}.

As the spectrophotometric standard W485 A (Oke 1974) has been observed on the same night, we were able to determine the intensities of the nebular emission lines, F^0, in both positions of the slit (Table 1); the value for Hγ was very uncertain. We have estimated that about 75 per cent of the light of the standard star passed through the diaphragm used. In order to obtain the intensities corrected for reddening, F^c, we applied the extinction coefficient $c = 0.775$ (Cahn & Kaler 1971) and the reddening function $f(\lambda)$ as given by Kaler (1976). The excitation class ⩾ 10 then follows from the intensity ratios I(λλ 5007 + 4959)/I(Hβ) and I(λ 4686)/I(Hβ) (Aller & Liller 1968).

For the *UBV* photometry of the central star of K1–2 we used the ESO 1-m telescope (f/13.6) with the EMI 6256 tube. We observed on eight nights in 1979 and 1980 with results given in Table 2. The contribution of the nebular radiation to the *UBV* stellar magnitudes

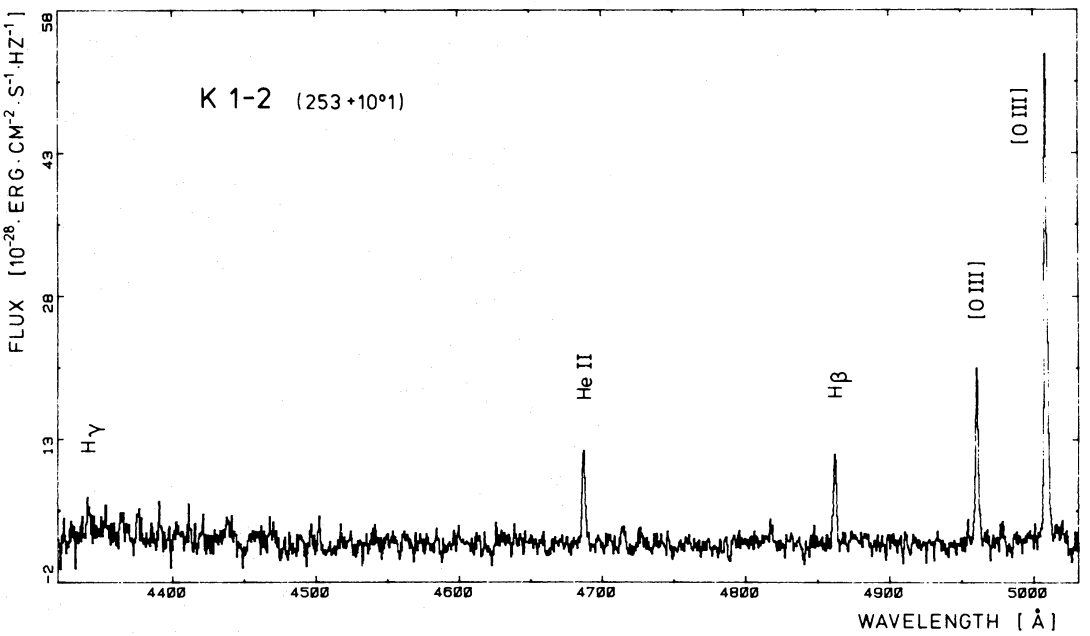

Figure 1. Mean spectrum of K1–2, λλ 4290–5050 Å (ESO 3.6-m telescope, B + C spectrograph + IDS, integration time 20 min). The observed nebular fluxes do not contain the correction for the fact that only part of the light of the standard star passes through the diaphragm used.

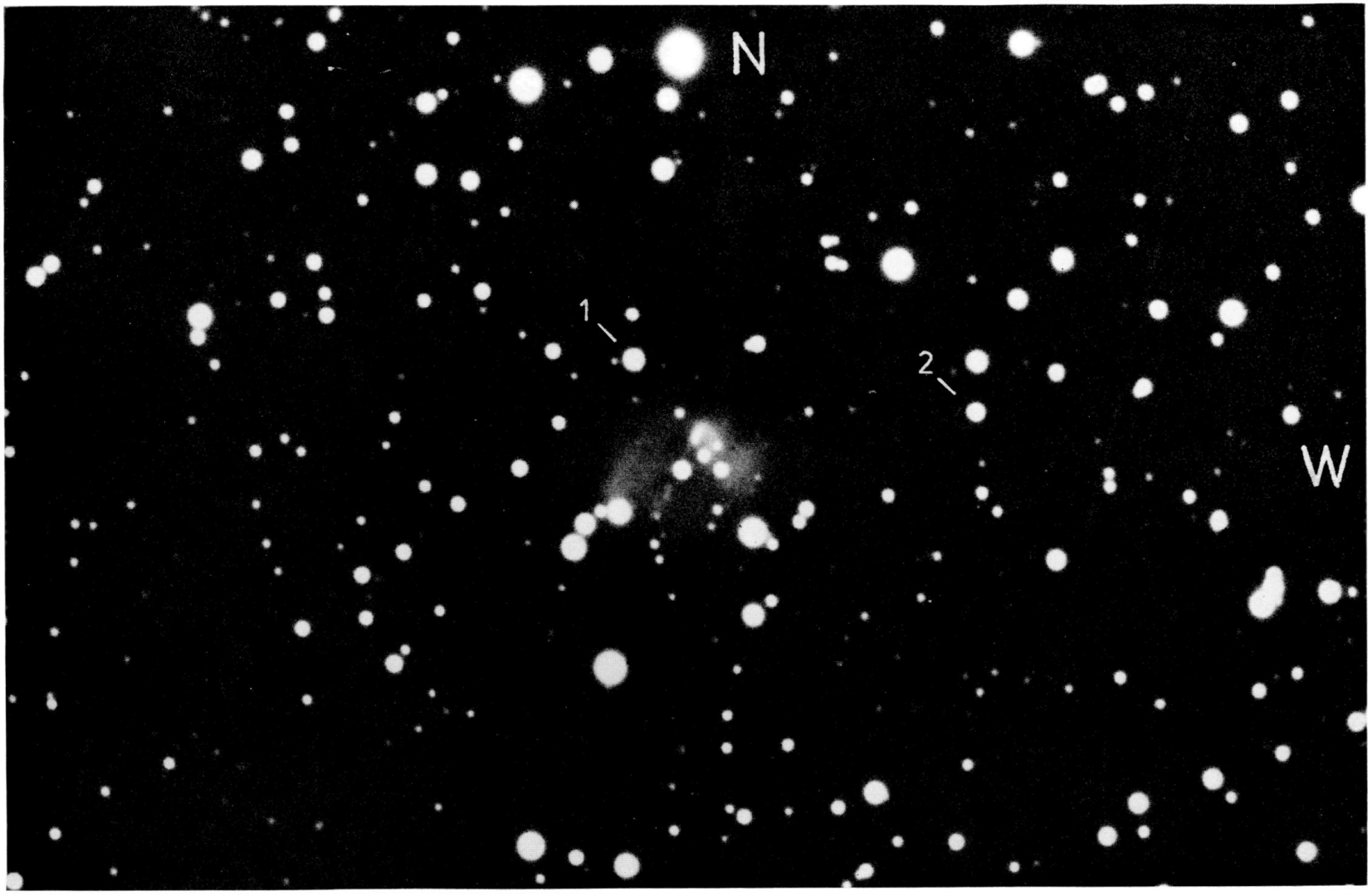

Plate 1. Photograph of K 1–2 taken at the prime focus of the ESO 3.6-m telescope ($f/3$, scale = 18.9 arcsec mm^{-1}) on 1978 April 8, (Kodak IIIa-J+ GG 385, exposure 40 min). Scale = 2.7 arcsec mm^{-1}. The two photometric comparison stars are marked.

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Table 1. Intensities of the nebular emission lines.

Line	$F^o \times 10^{16}$ [erg cm^{-2} s^{-1}] 20"E	20"W	f(λ)	F^c(mean) [$F^c(H\beta) = 100$]
[O III] 5007	29.1	53.6	−0.032	524
[O III] 4959	9.5	18.6	−0.021	182
Hβ	6.2	8.6	0.0	100
He II 4686	6.4	9.2	+0.044	113
Hγ	2.4:	2.8:	+0.133	44:

Table 2. *UBV* photometry of the central star of K1–2 in 1979 and 1980.

$JD_\odot$ 2440000+	V	B	U
3963.606	>17.2	17.20	16.08
.645	>17.2	17.32	16.41
3964.525	17.32	17.34	16.39
.549	17.32	17.44	16.33
3965.535	16.57	16.70	15.62
.587	17.05	17.01	15.73
.688	>17.5	17.59	16.64
4380.493	16.53	16.47	15.44
.512	16.67	16.71	15.61
4381.528	>17.5	17.58	16.63
.550	>17.5	17.74	16.50
4382.476	>17.2	17.07	16.09
.498	16.81	16.65	15.71
.576	16.51	16.54	15.35

was eliminated by setting the diaphragm (16 arcsec) inside the image of the nebula. The assumption of the homogeneous brightness of the nebula was fulfilled in the first approximation (see Plate 1). Two comparison stars were observed close to K1–2 as indicated on Plate 1. All measurements were referred to the photometric standard stars from the E-regions E4, 5, 6 and 7 (Cousins 1973). The mean brightness and colours of the central star of K1–2 as well as of the comparison stars are given in Table 3 (n – number of measurements). The colours of the central star confirm our spectroscopic results and indicate a nucleus of a very high temperature.

Table 3. Mean brightness and colours of the central star of K1–2 and of the comparison stars.

Star	V	B–V	U–B	n
K 1-2	16.5 ->17.5	+0.01	−1.09	8
m.e.		±3	±4	
Comparison 1	15.11	+0.59	+0.01	7
m.e.	±2	±2	±2	
Comparison 2	16.06	+0.68	+0.21	10
m.e.	±3	±3	±4	

As a by-product of the photometry of the central star the *UBV* brightness of the nebula in a circle of diameter 16 arcsec could be estimated. We obtain the following values from 10 settings:

$V = 18.04, \pm 0.17$, $B = 18.34, \pm 0.12$, $U = 17.68 \pm 0.14$.

The nebula seems to radiate strongly in the U region ($\lambda < 4000$ Å).

3 Light variability of the nucleus

The brightness of the central star varies in B between 16.5 and 17.7 mag as given in Table 2. No significant difference in $B-V$ and $U-B$ has been found between the maximum and minimum phase. Although our data do not allow a detailed analysis of the light curve we tried to confirm the period of Bond (1979). We assumed the light curve to be a one-cycle sinusoid and searched for a period in the interval 0.64–0.70 day (steps of 0.001 day) separately for the 1979 and 1980 observations; only B magnitudes were used. Our best solutions are summarized in Table 4, where T_{max} is the time of the maximum (phase 0),

Table 4. Mean parameters of the B light curve of the planetary central star.

Year	T_{max} $JD_{\odot} + 2440000$	P [days]	A [mag]	B_o [mag]
1979	3963.425 ±13	0.668 ±6	1.26 ±19	17.07 ±5
1980	4379.861 ±34	0.688 ±24	1.19 ±30	17.11 ±7

P – period, A – amplitude, B_0 – mean brightness (the brightness corresponding to phase 0.25). Combining the results from 1979 and 1980 we find $P = 0.669$ day, $A = 1.24$ mag, $B_0 = 17.08$ mag. If we combine $T_{max}(1979)$ with $T_{max}(1980)$ we obtain the following possible periods close to our mean P: 0.67167, 0.67059, 0.66951, 0.66844, 0.66737 day (± 0.00006 day), corresponding to 620, 621, 622, 623 and 624 cycles, respectively.

4 Main parameters of the nebula and of the central star

We applied the well-known statistical method based on the assumption of the constant nebular mass (Shklovskij 1956) in order to estimate the distance of K1–2:

$$\log d[\mathrm{pc}] = \log K - 0.2 \times \log F^c(\mathrm{H}\beta) - 0.6 \times \log r_n'' . \quad (1)$$

We adopted $K = 83$ which is the arithmetic mean of the recent distance scales (see Kohoutek & Martin 1981) and identical with the value recommended by Liller (1978). We took $r_n = 30.2$ arcsec for the mean angular radius of the nebula (geometric mean) and $\epsilon = 1$ for the filling factor.

The nebular flux in Hβ observed through the diaphragm 4 x 1.8 arcsec was $\log F_{obs}(\mathrm{H}\beta) = -15.13$; when extrapolating for the whole nebula and adopting $c = 0.775$ we obtained the corrected flux $\log F^c(\mathrm{H}\beta) = -11.74$ and, according to (1), the distance $d = 2.4$ kpc, very close to the value derived by Cahn & Kaler (1971). The size of the main nebular body is then

0.80 x 0.62 pc and the total extent of the nebula is nearly 1.3 pc. We have estimated that the uncertainty of the nebular distance and size does not exceed 20 per cent.

The effective temperature T_z and the luminosity L_* of the central star were derived using the procedure of Harman & Seaton (1966). The luminosity parameter $\Lambda = L_*/L_\odot \times d^2$ (d in kpc) is then expressed as a function of the effective temperature, the corrected nebular flux in Hβ, He II 4686 and the flux in the stellar continuum.

The relations for the nebular emission lines were taken from Kohoutek & Martin (1981, equations 10 and 13), where $t_e = 1$ (assumed) and $F_1(t)$, $F_4(t)$ are given by Harman & Seaton (1966). The flux in the stellar continuum was obtained from the observed brightness V ($\lambda_{eff} = 5470$ Å) and B ($\lambda_{eff} = 4330$ Å) and from the Hayes–Latham calibration of Vega (Hayes & Latham 1975):

$$\log F_*^c(5470) = -0.4 \times V - 8.449 + 0.864\,c$$
$$\log F_*^c(4330) = -0.4 \times B - 8.151 + 1.136\,c. \qquad (2)$$

Then

$$\log \Lambda = 13.365 + \log F_*^c(5470) + 4 \log t_z + \log [\exp(2.632/t_z) - 1],$$
$$\log \Lambda = 12.860 + \log F_*^c(4330) + 4 \log t_z + \log [\exp(3.325/t_z) - 1], \qquad (3)$$

$t_z = 10^{-4} T_z$, where the numerical constants followed from the effective wavelength of the V and B system respectively.

The solutions resulting from the diagram $\log \Lambda = f_i(\log t_z)$ are given in Table 5 separately for the maximum and minimum brightness of the central star. The stellar temperature T_z (He II) = $^{79\,000\text{ K (max)}}_{91\,000\text{ K (min)}}$ agrees with the highest nebular excitation class found from the intensity ratios of the nebular lines and the stellar radius (provided the star radiates as black-body) has a value corresponding to a subdwarf. The nebula is optically thin for the H I continuum (see Harman–Seaton parameter $\eta(\tau_1)$).

Table 5. Parameters of the central star.

	log $L_*/L_\odot$	log T_z (HeII)	log $\eta(\tau_1)$	$R_*/R_\odot$
MAX	3.00	4.905	-1.425	0.17
MIN	2.70	4.970	-1.110	0.09

5 Conclusions

K1–2 has been recognized to be a high excitation (excitation class $\geqslant 10$) old planetary nebula at a distance of about 2.4 kpc. Its nucleus is a blue subdwarf ($B-V = +0.01$, $U-B = -1.09$) having a luminosity 500–1000 $L_\odot$, of effective temperature (He II) 91 000–79 000 K and radius 0.09–0.17 $R_\odot$. The optical variability of the central star in the range 16.5–17.7 mag (B and V mag) has been confirmed. Our photometric data do not contradict the period 0.6707 day found by Bond (1979); however, they are too scarce for detailed analysis of the light curve.

Acknowledgments

We wish to thank the staff of the European Southern Observatory, La Silla, Chile, for assistance, Professor J. Hazlehurst for kindly reading the manuscript and Mrs D. Heymen

for her technical help. Dipl. Phys. R. Pauls helped us by searching for the period of the light variability of the nucleus using the computing program which kindly had been provided by Dipl. Phys. Th. Kleine.

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