HaTr 10, a Planetary Nebula with Extremely Strong Nitrogen Lines

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ABSTRACT

Optical spectra and direct images reveal that a very faint scarcely studied object (HaTr 10) which appears as an incomplete elliptical ring of $0\farcm4 \times 0\farcm2$ is a heavily obscured planetary nebula with exceptionally strong nitrogen lines ([N II] 6583 Å)/H$\alpha \approx 6$). In the Hα/[N II] vs. Hα/[S II] diagnostic diagram the object does not resemble H II regions or supernova remnants. It is quite far from the locus of the bulk of (bipolar) planetary nebulae. Photoionization models can well reproduce the observed emission lines, by using a gas of density 500 cm^{-3}, and with abundances of N = 8.6, O = 8.2, and all other elements with solar abundances. On our deepest CCD frames the nebula is considerably larger ($1\farcm5 \times 1\farcm0$), showing butterfly-like faint extensions. These symmetrical lobes, the ring around its waist, and the very high nitrogen abundance support the classification of HaTr 10 as an extreme bipolar planetary nebula. We suggest to obtain very deep frames of nebulae that appear morphologically akin to HaTr 10 to enable or support a reliable classification.

KEY WORDS: planetary nebulae: individual (HaTr 10) — techniques: spectroscopic

1. Introduction

HaTr 10 = PNG 031.3-00.5 ($\alpha = 18^{\rm h}47^{\rm m}49\overset{\rm s}{.}1, \delta = -01°43'43''$; 1950) was suspected to be a planetary nebula (PN) candidate by Hartl & Tritton (1985). It was discovered on a very deep R plate taken at the 1.2 m U.K. Schmidt telescope and was described as an "egg-shaped ring, thicker and brighter on the south-western end" with dimensions of $0\overset{'}{.}6 \times 0\overset{'}{.}3$.

The identification of this small incomplete ring as a PN remained somewhat doubtful, because there are almost no known planetary nebulae of comparable morphology – except SwSt 3 (West & Schuster 1980). The "pure nitrogen ring nebula" PL 1547.3-5612 (Ruiz 1983) also strongly resembles HaTr 10 in shape, and was classified as either a possible nova shell or a possible PN (Ruiz 1986). The very similar morphology and the (very) strong nitrogen emission lines make the three nebulae appear to belong to a nitrogen-rich subgroup of bipolar PNe.

Bipolar planetary nebulae are associated with the highest mass progenitors of PNe; besides a distinctive morphology, they have a peculiar galactic distribution and kinematics, CO and H_2 detection rates, optical thickness and central star mass distributions, and N and He chemical abundances (e.g. Corradi & Schwarz 1995). Based on deep monochromatic images and on low and high resolution spectra we will demonstrate that HaTr 10 has some extreme properties and will thus add to our understanding of this intriguing class of PNe.

2. Observations

Spectroscopic observations were carried out on May 3, 5 and 7 (five low-dispersion spectra; LDS) and on March 26, 1995 (one high-dispersion spectrum; HDS) with the Cassegrain spectrograph of the 74-inch telescope at the Okayama Astrophysical Observatory.

A grating of 150 lines/mm was chosen corresponding to a dispersion of 240 Å/mm for the LDS and 1800 lines/mm corresponding to 20 Å/mm for the HDS. The CCD device was a PM-516A with a pixel size of $20 \times 20\,\mu$m, or 4.8 Å in the direction of dispersion and $0\farcs72$ along the slit for the LDS; for the HDS the pixel size corresponds to 0.4 Å and $0\farcs72$, respectively. The slit dimensions were $300'' \times 1\farcs8$. The wavelength resolution is 2 Å for the LDS and 0.16 Å for the HDS (0.4 pixel).

The five LDS had exposure times between 30 and 60 min and a wavelength range 4400 – 6800 Å. The HDS had an exposure time of 30 min and comprised the range 6460 – 6660 Å. All spectra were placed E – W and covered the brightest (i.e. south-western) part of the ring. As standard star we used Kopf 27; Ne-Fe comparison spectra of a hollow cathode tube were taken. Bias and dome-flats were obtained and taken into account in the usual way. The reduction and analyses were made by use of the standard IRAF software package run on a UNIX work-station. The wavelength calibration was done by third order polynomial fits. The velocity error in the HDS was estimated to be about ± 7 km s^{-1} (± 0.4 pixel) or ± 0.16 Å.

In the course of a back-up program HaTr 10 was observed with the ESO 3.6 m telescope using the EFOSC 1 instrument. On June 27, 1995, four narrow-band images in H_α + [N II] (ESO filter #691, bandwidth 80 Å) of 5, 10, 60, and 600 sec, and two images in [O III] 5007 Å (#686, 59 Å) of 60 and 600 sec were obtained and reduced in the usual way; the spatial resolution is $0\farcs61$/pixel. Due to the poor weather conditions no flux calibration was attempted.

3. The Images

The highly elliptical shape of the nebular shell is evident on the broad-band R image presented in Hartl & Tritton (1985). On the reproduction of the broad-band J plate (which peaks near 4800 Å and includes the region of the 4959 and 5007 Å lines of [O III]), the nebula is hardly visible at all.

In Fig. 1, we present a mosaic of 4 CCD images of HaTr 10, taken in Hα + [N II] 6583 Å and [O III] 5007 Å. In the short-exposure Hα image (a), the ring appears to be well-defined in the south-west and there is a bar-like structure visible too. The [O III] image (b) shows a hook-like emission being less extended compared to (a); also, there is a faint, diffuse, roughly circular emission. We note that this image has a striking similarity to the [O III] image of Hf 4 (Schwarz, Corradi, & Melnick 1992).

In the medium-exposure Hα image (c), ring and bar are also evident, but embedded in a dim wide-spread emission. The long exposure (d) shows a nearly "filled" nebula of $\approx 0\overset{\prime}{.}5$ size, as well as butterfly-like extensions to the west/north-west and to the east/south-east. This image clearly shows that HaTr 10 is one of the "ringed" bipolar PNe. In none of the images we noted any trace of a central star.

4. The Spectra

Our low-dispersion spectra show a few emission lines only and are consequently not presented here. We find the prominent lines of [N II] 6583 + 6548 Å, Hα, the very faint [S II] 6717 + 6731 Å lines, of about equal intensity, and possibly a very faint [O III] 5007 Å line. The latter has a strength of 2.4% of [N II] 6583 Å, S/N = 1.6, and can therefore not be considered as a firm detection. We do not provide fluxes or line ratios from the LDS, since the lines are too faint to allow reliable measurements; ratios of the three bright lines were derived from the high-dispersion spectrum and are given below.

There exists an old, deep, low-dispersion photographic spectrum shown in Hartl & Tritton (1983). Only provisional line ratios (of [O III] 4959 + 5007 Å, [N II] 6583 + 6548 Å, Hα, [S II] 6717 + 6731 Å all relative to Hβ) were given without any further discussion. Also, the intensities of [O III] 5007 Å, Hα, [N II] 6583 Å, and [S II] 6717 + 6731 Å are given in Acker et al. 1992 based on the spectrophotometric survey by B. Stenholm. The line ratios of the two spectra agree quite reasonably. In particular, the values for [N II]6583/Hα of 5.6 and 4.9, respectively, agree well with the ratio of 6.0 from our HDS. Therefore, we make use of these "old" data in our analysis too. The data from Acker et al. 1992 – given with respect to Hα – are combined with the ratio Hα/Hβ = 15.5 observed by Hartl & Tritton (1983), to make a composite spectrum. The resulting line intensities are compiled in Table 1 together with the data for PN G321.6 + 02.2 by Corradi et al. (1997).

Our high-dispersion spectrum is shown in Fig. 2; the spike near 6592 Å is due to cosmics. The line ratio [N II] 6583/6548 is 3.1, in quite good agreement with the theoretical value of 2.94 (Acker et al. 1989b). As this ratio is determined by the atomic branching ratio only, this confirms the good quality of the observational data. The line ratios of [N II] 6583/Hα, and ([N II] 6583+6548)/Hα are found to be 6.0, and 7.9. For the heliocentric radial velocity we get +41 (6548), 43 (Hα), and 44 (6583) km s^{-1} ($\pm$7 km s^{-1}). The width of the lines (4, 8, and 6 $\pm$7 km s^{-1}, respectively) are consistent with pure Doppler broadening effects near 10 000 K.

5. The Nature of HaTr 10

The position of HaTr 10 does not coincide with that of any IRAS or radio source. The nebula has a considerable interstellar extinction: from the line ratio Hα/Hβ = 15.5 in Hartl

& Tritton (1983) one obtains an interstellar extinction of $E_{\rm B-V} = 1.5$ or $A_{\rm V} = 4.8$ mag. Unfortunately, the whole region close to the object shows a complex pattern of optically visible dust clouds, thus preventing the application of the reddening-distance method to estimate the distance of HaTr 10.

The most conspicuous characteristic of the spectrum of HaTr 10 is the high [N II]/Hα intensity ratio. Though very high [N II] to Hα ratios are rare among planetary nebulae, there are several examples like the bipolar PN G321.6 + 02.2 found by Corradi et al. (1997). The extraordinary strength of the nitrogen lines is evident when comparing HaTr 10 with other objects: In the diagnostic diagram of (Hα/[N II]) vs. (Hα/[S II]) shown in Fig. 3 after Corradi et al. (1997) one finds that HaTr 10 – based on our own data and those of Acker et al. 1992 – belongs neither to the class of H II regions nor supernova remnants. Its locus is quite distant from that of the majority of planetary nebulae, and also of most bipolar PNe.

While bipolar PNe usually have stronger nitrogen lines than common PNe, it appears obvious that HaTr 10 is one of the extreme members of this class. The most extreme example, in the lower left corner of Fig. 3, is PN G321.6 + 02.2: Corradi et al. (1997) find a bipolar morphology, a giant size ($\sim$ 4 pc), low density (250 cm^{-3}), and a hot (unobserved) central star (T >130 000 K). In the diagnostic diagram the other objects are not identified, but inspection of the spectra of Perinotto & Corradi (1998) shows that NGC 2899 and He 2-111 have nitrogen lines as strong as in HaTr 10.

In Table 1 we compare the observed spectrum of HaTr 10 (Acker et al. 1992) with that of PN G321.6 + 02.2 by Corradi et al. (1997). Though the extinctions are different, it is evident that the line ratios are quite similar: [O III] as strong as usually found in fairly high excitation PN, very strong [N II], and [S II] lines stronger than in normal PN. In HaTr 10 the higher reddening as well as the low surface brightness did not allow a measurement of the He II 4686 Å line whose presence could confirm the relatively high excitation.

The data available allow some preliminary physical interpretation: The spectra of Acker et al. 1992 and Hartl & Tritton (1983) show an intensity ratio of the [S II] 6717/6731 Å lines of about unity. Such a value gives an electron density of 580 cm^{-3} for an electron temperature of 10 000 K and performing the usual plasma diagnostics (with the code HOPPLA, cf. Acker et al. 1989a). The observations of Stenholm also gave an Hα line flux of $1.74\,10^{-17}$ W m^{-2} (Acker, priv. comm.). With Hα/Hβ = 15.5 from Hartl & Tritton (1983) on gets F(Hβ) = $1.12\,10^{-18}$ W m^{-2}. Correcting for the interstellar extinction from above and for the $4{\times}4''$ aperture used by assuming that the surface brightness is constant over the circular disk of a diameter of $\approx 25''$ from Hartl & Tritton (1985), we get a total dereddened Hβ flux of $6.52\,10^{-15}$ W m^{-2}.

All these data can be reproduced by a Strömgren sphere (with electron temperature 10 000 K) at a distance of 1.5 kpc and around a star emitting $3.43\,10^{45}$ photons/sec, for example a central star with 100 000 K and a luminosity of 47 $L_{\odot}$. At 1.5 kpc the maximum diameter of the nebula ($1\farcm5$) would correspond to 0.7 pc, quite a reasonable value for a highly evolved PN.

A more complete analysis can be done by constructing photoionization models which permit to predict what the physically consistent spectrum of a nebula would be, and how it depends on the temperature and luminosity of the central star and of the properties of the nebula shell, viz. its density and chemical composition. We use the code GWYN (Köppen 1979; Rauch, Köppen, & Werner 1996) to compute the ionization and thermal balance in spherically symmetric nebulae. The density is taken to be constant throughout the nebula. To represent bipolar nebulae with such a geometry is certainly a simplification, probably for the lines which come from the outer lobes as compared to those produced in the denser waist. But since the ionization structure depends more strongly on stellar properties than on nebula density (Köppen 1979), this approach is expected to give still quite reliable models. Moreover, in doing this one does not only avoid the additional computational effort involved with a two-dimensional code but also the problem of determining the spatial structure of the shell. With the little information available, such an effort was deemed not to be worthhile.

We computed grids of ionization bounded models – using the on-the-spot approximation for the diffuse ionizing radiation. We vary the temperature (between 33 000 K and 150 000 K) and luminosity (100, 1000, and 10 000 $L_\odot$) of the blackbody central star. For the nebula density we take two extreme values: 10 and 10 000 cm^{-3}. The calculated line intensity ratios are shown in the diagnostic diagrams of Hα/[N II] vs. Hα/[S II] (Fig. 3) and Hα/[N II] vs. [O III]/Hβ (Fig. 4).

In Fig. 3, all models with a solar nebular abundance are found along a rather well defined path passing through the region of supernova remnants and touching that of H II–regions and planetary nebulae. While the range in Hα/[S II] is quite comparable exhibited by the bipolar PNe, the nitrogen lines in these models are about 3 times weaker than in HaTr 10 and other extreme bipolar PNe. Increasing the temperature or luminosity of the central star or decreasing the density of the nebula shell all decrease both Hα/[N II] and Hα/[S II] ratios, the temperature being the most important parameter.

In Fig. 4, depicting Hα/[N II] vs. [O III]/Hβ the strong sensitivity of the [O III]/Hβ ratio on stellar temperature – and far less on luminosity or density – is clearly evident. Thus, in both HaTr 10 and PN G321.6 + 02.2 the star should be fairly hot, $T \approx 100\,000$ K.

For another model grid we increase the abundance of nitrogen by 0.5 dex above the solar value as well as decrease oxygen by the same amount. These models (with abundances of N = 8.57 and O = 8.33) all have nitrogen lines stronger by about this factor, and are more satisfactory to explain nebulae such as HaTr 10 and PN G321.6 + 02.2 (Fig. 3). The decrease in oxygen abundance is quite necessary for matching the strong nitrogen lines:

If we increase only the nitrogen abundance by 0.5 dex, the enhanced cooling reduces the electron temperatures by typical 500 to 1000 K, and thus the intensity of the [N II] linee increases by only 0.2 to 0.3 dex. Lowering the oxygen abundance raises the electron temperature by about 1000 K and thus the [N II] intensity by a further 0.1 dex. Figure 4 shows that consequently the[O III]/Hβ ratios tend to be somewhat smaller, thus making the required central star temperatures even higher. The value of 130 000 K derived by Corradi et al. (1997) from the energy balance method thus might well be a lower estimate.

The behavior of the line ratios is the combined result of the ionization structure and line excitation: increasing stellar temperature and the product $R_*^2 n$ of stellar radius (i.e. luminosity) and nebular density will raise the ionization in the nebula (Köppen 1979). Consequently, [O III] becomes stronger, while [N II] and [S II] grow weaker. The latter two lines are also affected by collisional deexcitation for densities above several 1000 cm^{-3} which causes a further decrease. Altering the chemical composition affects directly the line intensities of the elements involved, in about the same proportion as the abundance changes. Finally, the cooling function and thus the resultant electron temperature is changed, as can be seen in Fig. 3 as an increase of Hα/[S II] by almost 0.5 dex. The reason is that additional cooling by nitrogen lines results in a lower electron temperature and less collisional excitation.

We note that the models of both grids are confined to two rather narrow bands in the diagnostic diagram of Hα/[N II] vs. Hα/[S II which are well separated from each other. This may well suggest that the sequence of bipolar nebulae of increasing [S II] and [N II] lines is in fact associated with a systematic increase of the nitrogen abundance. Such a behavior could well be the consequence of the central star's progenitor becoming more massive along this sequence, thus showing pollution of the nebula gas by the products of stellar nucleosynthesis, viz. helium, carbon, and nitrogen.

Because of the strong influence of the chemical abundances on all forbidden lines intensities via the cooling function, fitting a detailed individual photoionization model for HaTr 10 is not sensible, given the rather incomplete and limited observational data. Nonetheless, we constructed an approximate model which can well reproduce the [N II], [O III], and [S II] lines with a nebula of gas density of 500 cm^{-3} and with abundances of $N = 8.7 \pm 0.1$ and $O = 8.0 \pm 0.1$ with all other elements having solar abundances ($C = 8.56$, $Ne = 8.03$, $S = 7.19$, and $Ar = 6.56$). The ranges given refer to the interval within which one matches the nitrogen and oxygen lines within about 10%, but are not proper error bars, because changing either abundance alters the intensity of both lines. The central star is assumed to have a temperature of 100 000 K and a luminosity of 50 $L_\odot$, taken from our preliminary analysis. Unfortunately, the highly reddened spectrum is too weak in the blue to measure or even get an indication for the presence of the He II 4686 Å line which would be the only safe constraint on the stellar temperature.

In this model, the electron temperature in the N II-zone is 9800 K, and in the O III 10700 K. Increasing the N-abundance by 0.1 dex results in [N II] lines stronger by 8%, [O III] lines weaker by 13% and both electron temperatures lower by 350 K. Increasing the O-abundance by 0.1 dex gives [N II] lines weaker by 2%, [O III] lines stronger by 20%, and electron temperatures lower by 100 K. This behaviour shows that in HaTr 10 the [N II] lines are quite dominant in the cooling function, rather than the [O III] lines as in nebulae with a more 'normal' chemical composition.

In summary, HaTr 10 appears to be a genuinely nitrogen-rich planetary nebula with a bipolar morphology. It resembles both SwSt 3 and the "pure nitrogen ring nebula" PL 1547.3-5612 both of which also show a highly elliptical ring with enhanced surface brightness at the ends of the major axis. These could well form a subclass of extreme bipolar planetary nebulae. We expect that very deep images will exhibit butterfly-like envelopes around SwSt 3 and PL 1547.3-5612. The latter might then turn out to be the most extreme N-rich example of a bipolar planetary nebula.

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Fig. 1.— Monochromatic images of HaTr 10: frames a, c, d are images in [N II] + Hα with exposure times of 10, 60, and 600 sec. Frame b is an image taken in [O III] with 600 sec exposure time. North is at top, east to the left. Each image is $2\farcm3 \times 2\farcm9$ across.

Fig. 2.— High dispersion spectrum of HaTr 10. The slit was placed E-W across the brightest part of the nebula. The feature near 6592 Å is due to cosmics.

Fig. 3.— The log(Hα/[N II]) vs. log(Hα/[S II]) diagnostic diagram after Cantó (1981), with positions of 20 bipolar planetary nebulae (dots) from Corradi et al. (1997). The large dot at the extreme lower left is PN G321.6 + 02.2. The large crossed circle represents HaTr 10; its size indicates the range in the observed line ratios. The other symbols refer to photoionization models with stellar temperatures of 33 000 (open circles), 50 000 (triangles), 75 000 (squares), 100 000 (X), and 150 000 K (+); small points indicate intermediate temperatures; the size of the symbols increases with stellar luminosity from 100, 1000, and 10 000 $L_{\odot}$. Lines connect the models with a nebula density of 10 cm^{-3}, the group of symbols to the upper right are models with a density of 10^4 cm^{-3}. The upper model grid is done for nebulae with solar composition, the lower one is with nitrogen enhanced by 0.5 dex and oxygen lower by 0.5 dex.

Fig. 4.— The log(Hα/[N II]) vs. log([O III]/Hβ) diagnostic diagram. The meaning of the symbols is the same as in Fig. 3. Also, the models with solar composition and a density of 10^4 cm^{-3} are connected by dashed lines.

Table 1. The observed line intensities of HaTr10 (Acker et al. 1992 using the Hα/Hβ ratio from Hartl & Tritton (1983)) in comparison with those of PN G321.6 + 02.2 by Corradi et al. (1997). The Hβ fluxes are given in units of 10^{-18} W m^{-2}

line	HaTr10	321.6 + 02.2
F(Hβ)	1.12	3.07
He II 4846	?	45
Hβ 4681	100	100
[O III] 4959	280	256
[O III] 5007	880	792
[N II] 6548	2380	2061
Hα 6563	1550	684
[N II] 6583	7530	6376
[S II] 6717	500	313
[S II] 6731	430	264