

# SBS 1150+599A: An extremely oxygen-poor planetary nebula in the Galactic halo?

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**Abstract.** We report results of a spectrophotometric study of SBS 1150+599A and discuss the nature of this object based upon our data. Our study shows that SBS 1150+599A is most probably a planetary nebula located in the Galactic halo and not a cataclysmic variable as originally proposed by the authors of the Second Byurakan Survey from low resolution spectroscopy. We have further elaborated on the properties of SBS 1150+599A (now becoming PN G135.9+55.9) with tools used for planetary nebula analysis. Our photoionization models show that, in order to match the observational constraints, the oxygen abundance in the nebula is probably extremely low, around 1/500 solar, which is one order of magnitude lower than the most oxygen-poor planetary nebulae known so far. This finding has strong implications on our understanding of the formation of planetary nebulae and of the evolution of the Galactic halo.

**Key words.** ISM: planetary nebulae: general – ISM: planetary nebulae: individual: SBS 1150+599A (PN G135.9+55.9), – galaxies: halos – stars: binaries: symbiotic – stars: cataclysmic variables

## 1. Introduction

SBS 1150+599A pertains to the list of stellar-like objects from the Second Byurakan Survey (SBS) (Balayan 1997; Stepanian et al. 1999). The Second Byurakan Survey is a low resolution objective prism survey with a limiting magnitude of  $B \sim 19^m.5$  (Stepanian 1994; Bicay et al. 2000). The observing technique and the selection criteria for the SBS objects have been described by Markarian & Stepanian (1983), Markarian et al. (1987), and Stepanian (1994a, 1994b). Worth mentioning is that the selection criteria of the SBS include the presence of a strong UV continuum, emission lines, and/or peculiar energy distribution as inferred from the objective prism spectra. These criteria have been successful in selecting objects such as UVX galaxies (Markarian galaxies), as well as a broad class of AGNs (Carrasco et al. 1998; Stepanian et al. 1999). As a by product, a large number of

peculiar stars, WDs, composite and emission objects, hot subdwarfs and other types of objects have been detected (Balayan 1997; Stepanian et al. 1999). Among them several new Cataclysmic Variables (CV) were discovered.

Here, we report on a spectrophotometric study of SBS 1150+599A in order to clarify its nature. This object is located at a very high Galactic latitude:  $l_{\text{II}} = 135.96$ ,  $b_{\text{II}} = 55.94$ . It was first thought to be a CV based upon the appearance of its spectrum. It shows strong hydrogen and helium lines superposed upon a hot continuum, a characteristic pattern for CVs. Later, in a short communication, Garnavich (1999) claimed that SBS 1150+599A is a symbiotic star or a young planetary nebula. Our study shows that this object is not a CV or symbiotic, but probably a peculiar and rather old halo Planetary Nebula (PN).

In Sect. 2, we present the data acquisition and reduction processes, in Sect. 3 we derive the observational parameters for SBS 1150+599A. In Sect. 4 we discuss the various hypotheses about the nature of SBS 1150+599A, and in Sect. 5 we perform a photoionization modeling of the object, bringing constraints on the oxygen abundance and temperature of the exciting star. In Sect. 6 we discuss some implications of our work.

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**Table 1.** The log of spectral observations

Date UT	JD	Telescope + Equip.	Wavelength Range	Number of spectra	Exp. sec.	Site
1998 March 20	2450892	2.1 m, B&Ch+CCD2K	3600–6200	10	900/1200	SPM
1998 June 06	2450971	2.5 m, IDS+CCD TEK3	4600–5500	2	1200	La Palma
2000 March 19	2451622	2.1 m, LFOSC+CCD	4000–7170	2	1800	Cananea
2000 April 11	2451645	2.1 m, B&Ch+CCD TEK1	3700–7500	3	1200	SPM
2000 April 12	2451646	6.0 m, UAGS+PMCCD	3600–8260	1	900	SAO

## 2. Data acquisition and reduction

SBS 1150+599A was observed with the 6 m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences (SAO RAN) in 1986. The observations were carried out with the SP-124 spectrograph equipped with a 1024-channel photon counting system (IPCS) (Drabek et al. 1985), installed at the Nasmith I focus. No flux calibration is available. Based upon that low resolution spectrum, SBS 1150+599A was classified as a CV (Balayan 1997; Stepanian et al. 1999).

Recently we acquired a new spectrum of the object on the 6 m telescope with the UAGS spectrograph and a CCD detector. Although we obtained the necessary spectrophotometric standards, the sky conditions were poor for correct absolute flux measurements. The spectrum was obtained in the 3600–8260 Å range with a spectral resolution of 4.65 Å/pix which, combined with the deployed slit width, gives overall resolution of 10 Å *FWHM*.

We also obtained a set of spectra of SBS 1150+599A with the 2.1 m telescope of the Observatorio Astronomico Nacional de San Pedro Martir (OAN SPM) on 20 of March 1998. The Boller & Chivens spectrograph was set in the 4150 to 6750 Å range with a resolution of 1.28 Å/pix corresponding to 4.8 Å *FWHM*. The slit was set to 1.8 arcsec. The seeing was poor. It was not possible to obtain standard stars for calibration during the same night. We used an averaged sensitivity curve for the corresponding grating and settings of the spectrograph to calibrate the data from this night.

Additional spectra of SBS 1150+599A were obtained at the 2.1 m telescope of OAN SPM on 11 of April 2000. This time we used a 300 l/mm grating with the same spectrograph in order to observe the object in the  $\lambda$  3700–7500 Å wavelength range with 8.0 Å *FWHM* resolution. During these observations, in order to cover a larger fraction of the object, we opened the slit up to 3.0 arcsec although the seeing was good and did not exceed 1.5 arcsec. Two spectrophotometric standards were observed along with the object and an He-Ar lamp was used as in the previous observations for wavelength calibration.

The object was also observed on one occasion with the 2.5 m Isaac Newton Telescope (INT) of Observatorio de La Palma. The IDS spectrograph was centered around the H $\beta$  region (4600–5500 Å). A spectral resolution of 1.6 Å was reached as measured from the *FWHM* of arc lines.

A Cu-Ar+CuNe lamp was used for wavelength calibration. No flux calibration is available.

We also acquired a low resolution spectrum of SBS 1150+599A at the 2.1 m telescope at Cananea, México in March of 2000. The LFOSC spectrograph (Zickgraf et al. 1997) was deployed to cover the  $\lambda$  4000–7100 Å wavelength range with  $\approx$ 13 Å *FWHM* resolution. The long slit was deployed at the entrance of this multi-object spectrograph 3 arcsec wide as projected on the sky.

For none of the observations was the slit oriented along the parallactic angle. Usually it was simply in East-West direction. For the SPM observations, due to the faintness of the object and absence of appropriate slit-viewing detector, pointing and subsequent guiding were not perfect and might cause inaccuracy of flux determinations.

Most of the observed data were reduced using IRAF packages after applying standard procedures for bias and flat field corrections. The observations acquired at SAO were reduced using the MIDAS system. The MIDAS cosmic rays cleaning procedure was also applied to the rest of the data.

The Journal of observations is presented in Table 1.

We performed an extensive search in publicly available surveys and databases for any additional measurements at the location of SBS 1150+599A. IRAS has no detection of any IR source within several arcminutes, even among rejected faint sources. No emission was detected at short wavelengths. Neither ROSAT RASS nor UV surveys show any emission within corresponding error boxes. Among radio surveys the closest registered source lies 6 arcmin away from the object.

## 3. Spectral analysis and observational parameters

The spectrum of the object displays a blue continuum with strong narrow emission lines of H I, He II and marginally detected [O III]. No trace of He I lines or lines from singly ionized ions of O, N or S are detected. In Fig. 1 the low/medium resolution spectra of the SBS 1150+599A are presented at different epochs.

The spectrum in the upper panel is the best flux-calibrated spectrum obtained at SPM with the wide slit (it is in reasonably good agreement with the latest SAO and Cananea spectra). In the inset of the upper panel the sum of 7 spectra (total exposure of 8400 s) from previous SPM observations is presented. It reaches a S/N ratio of 20 in the continuum around H $\alpha$ . The faint lines of

[O III]  $\lambda$  5007 Å and He II  $\lambda$  5411 Å appear clearly in that spectrum.

The shape of the continuum and of the line profiles do not change from epoch to epoch. There is a small discrepancy in absolute fluxes between spectra, but this could easily be a result of inadequate observational conditions rather than variability. This leaves open the question of the variability of the SBS 1150+599A.

In the lower panels of Fig. 1 the individual profiles of H $\beta$  and He II lines from the higher spectral resolution spectrum obtained at INT are shown. This spectrum, obtained with 1.5 Å resolution, demonstrates that the emission lines of the object are relatively narrow. The measured values of *FWHM* of H $\beta$  and He II are 2.0 Å and 1.85 Å respectively.

Another important spectroscopic feature is that the emission lines of SBS 1150+599A are displaced towards short wavelengths. This blue shift shows some dispersion from line to line and also from epoch to epoch.

Before we consider the measured fluxes, it is necessary to mention that the emission lines are spatially extended, which indicates an extended object. The edge to edge width of the line in the spatial direction on the INT spectrum is  $\approx 14$  pix, which corresponds to an object size of  $\approx 10''$ . A similar value is obtained from the SPM spectra.

Table 2 lists the parameters of the emission lines. Equivalent widths and relative fluxes were measured in all the acquired spectra and we decided to present the whole range of obtained values, which gives a good idea of the errors of measurement. The spread is up to 35% in some line fluxes, however relative numbers are usually more consistent among the various spectra. We found systematically lower values of the H $\alpha$ /H $\beta$  ratio in spectra obtained at SPM. We suspect that there were problems with the linearity of the CCD used in those observations and that the very intense H $\alpha$  line was veiled. We favor values closer to the upper limit (2.7) in Table 2. The ratios of lines comparable in intensity are in better agreement from different observations. In the case of absolute fluxes, we used the highest values obtained in the best (but not perfect) conditions. The same is true of *FWHM* and radial velocity shifts. We only present the values from the higher resolution spectra. Generally the resolution is not so relevant in the case of line center measurements. But we are doubtful about instrumental line profiles and prefer not to rely on them. It should be noted, however, that in all the low resolution spectra the blueshifts of the lines are higher.

#### 4. Nature of the object

The optical spectra of SBS 1150+599A that we have at our disposal do not permit us to classify it unambiguously into any known type of object. Below we will discuss the most plausible options and will seek to identify the nature of the object and model it.

##### 4.1. A Cataclysmic variable?

Although SBS 1150+599A was originally classified as a CV by the authors of the SBS, a careful examination of the spectra rejects such an interpretation completely. CVs are close binary systems where stellar components are white and red dwarfs, and the radiation is dominated by the outcome of accretion processes, usually through disc accretion. CV systems are observed mostly in our vicinity (100–500 pc). The emission lines originate in accretion discs, they are broad due to the dispersion of velocities in the disc, and show radial velocity variations on short terms, because of orbital motion in the binary (Warner 1995). Meanwhile, the emission lines of SBS 1150+599A are narrow ( $\leq 2$  Å) and they lack any structure or radial velocity changes on a nightly basis. Most importantly the lines show persistent blueshift of about 3 Å at all epochs. A CV with emission lines shifted to that extend should be a high inclination system, thus in a time span of several hours (5–6 hours are half of the longest period of CVs) should demonstrate significant radial velocity variations.

As mentioned above, in CVs one should expect much wider line profiles, due to the presence of an accretion disc or accretion flow. Accreting matter is the major source of light in CVs and even in magnetic CVs, where no disc is formed, emission lines should contain much broader components, variable with orbital phase (Schwope 1997).

Finally, CVs with strong He II emission as a rule contain also significant neutral helium and show strong emission of He I  $\lambda$  4471, 5876 Å, though they are not known to have any measurable [O III]  $\lambda$  5007 Å emission.

##### 4.2. A Symbiotic star?

The spectrum of SBS 1150+599A looks more like that of a symbiotic star (SS) than of a CV. SSs are binary systems that contain a giant secondary component (at least for 80% of them, the rest containing a Mira variable) instead of a late type dwarf as in CVs. They can be discovered at much larger distances, as far as in the halo or in the Magellanic Clouds. Quite a few SSs are known to be halo objects. They are also known to contain a variety of nebular lines ([O III], [Ne III], [Ne V] and [Fe VII]) not seen in CVs.

For years, symbiotic stars were a collection of strange objects. However starting from 80's, two catalogs of SSs and suspected objects were published (Allen 1984; Kenyon 1986) consolidating a group of characteristics necessary for an object to be classified as a symbiotic star. More recently in a new catalogue of symbiotic stars (Belcziński et al. 2000) the classification criteria of symbiotics were refined, based on a compromise between a large variety of features displayed by more than 180 objects classified as SSs.

The three basic characteristics that an object should fulfil in order to be classified as a SS are:

- the presence of absorption lines of a late type giant;

**Table 2.** Measurements of spectral lines

Emission Line	Equivalent Width Range (Å)	Flux <sup>a</sup> ( $\times 10^{-14}$ ) (erg cm <sup>-2</sup> s <sup>-1</sup> )	Relative Flux Range	$FWHM^b$ Å	Line Center <sup>c</sup> Shift (Å)
H $\epsilon$	-3-5	0.13	0.11-0.14	-	-
H $\delta$	-6-12	0.3	0.23-0.34	-	-
H $\gamma$	-16-18	0.67	0.41-0.57	-	-
H $\beta$	-50-80	1.19	1.0	2.0	-2.83
H $\alpha$	-400-600	3.01	2.46-2.9	-	-
He II $\lambda$ 4686 Å	-30-44	1.09	0.7-0.92	1.84	-2.68
[O III] $\lambda$ 5007 Å	-2-3	0.037	0.03-0.035	-	-
He II $\lambda$ 5411 Å	-5-7	0.064	0.05-0.065	-	-
He I $\lambda$ 5876 Å	-	-	< 0.01	-	-
[N II] $\lambda$ 6584 Å	-	-	< 0.005	-	-
[S II] $\lambda$ 6725 Å	-	-	< 0.005	-	-

<sup>a</sup> Flux measurements are based upon the highest values obtained from SPM 2000 observations with a wide slit.

<sup>b</sup> As measured on the higher resolution INT spectrum.

<sup>c</sup> The shifts as measured on the INT spectrum correspond to a heliocentric velocity of  $-190 \pm 2$  km s<sup>-1</sup>.

The shifts measured on lower resolution SPM spectra are systematically higher: of order of  $-260$  km s<sup>-1</sup>.

- the presence of emission lines of H I and He I in combination either with lines from ions with ionization potential  $\geq 35$  eV like [O III], or with a A-F type continuum with additional shell absorptions in hydrogen and helium lines;
- the presence of the  $\lambda$  6825 Å emission feature, even if no features of the cool star are observed.

SBS 1150+599A apart from having high ionization emission lines does not satisfy any other criteria established by Belczyński et al. (2000). Neither our spectra, nor available IR surveys provide any evidence for the presence of late giant in the immediate neighborhood of the object.

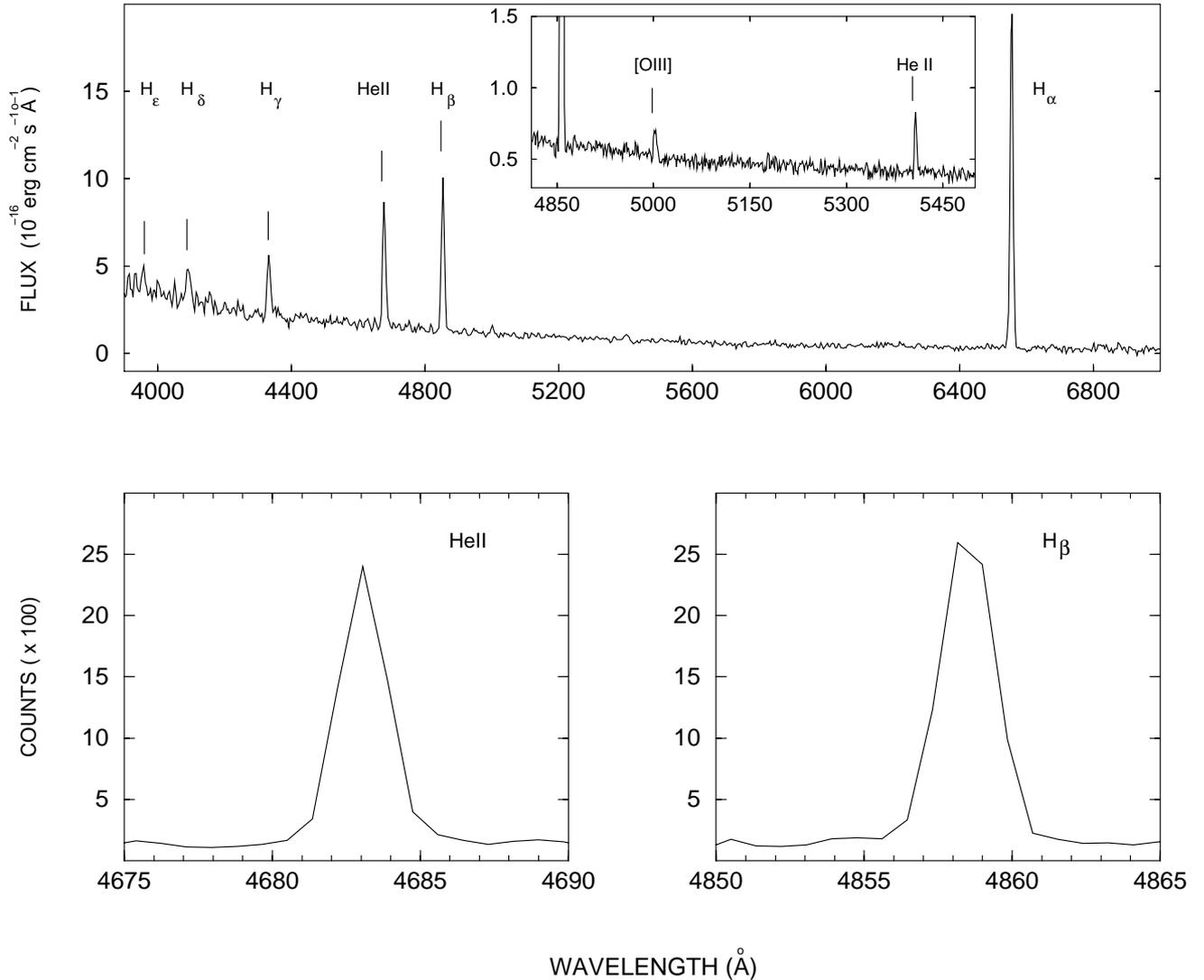
Another argument against a SS classification is that similarly to CVs, SSs exhibit complicated line profiles and strong variability. A broad component, in addition to the narrow component, should be observed at least in forbidden lines. Otherwise, if higher ionization lines are narrow and featureless, one should observe central reversals or other structures in the Balmer lines (see for example the atlas of high resolution line profiles of SSs of Ivison et al. 1994). Yet, the lines of SBS 1150+599A do not show any deviation from a single Gaussian profile or extended wings at the base in any of the observed epochs.

Taking into account these arguments, we find it very unlikely that the object in question is a symbiotic. However we cannot exclude this possibility completely. The uncertainty with the possible radial velocity variability of the lines leaves the question open until new extensive data can be collected.

#### 4.3. A Local Group galaxy?

The object being blue shifted, if it were a galaxy it would necessarily belong to the Local Group, implying that its distance would be  $< 1.2$  Mpc (van den Bergh 1999). From

the observed H $\beta$  flux, we deduce that the total H $\beta$  luminosity would be  $< 2 \cdot 10^3 L_{\odot}$ . This is much less than the typical H $\beta$  luminosities of H II galaxies, which range between  $10^{38}$ – $10^{41}$  erg s<sup>-1</sup> (Salzer et al. 1989). During the phase where O stars are present, an ionizing star cluster with a total mass of  $10^5 M_{\odot}$  (typically the mass of a globular cluster, Aguilar et al. 1988) produces about  $10^{51}$ – $10^{52}$  ionizing photons per second, according to stellar population synthesis models (Leitherer & Heckman 1995). This implies that, if such a cluster were powering our object, the surrounding gas would absorb only about 1/1000 of the available ionizing photons. There is no sign of the presence of large quantities of dust in this object (from the observed continuum and from the H $\alpha$ /H $\beta$  ratio) that would absorb the radiation, so most of the cluster's ionizing radiation would leak out. Qualitatively, this would explain why the observed He II  $\lambda$  4686 Å/H $\beta$  ratio is so high (in H II galaxies it is at most equal to a few percent, see e.g. Izotov & Thuan 1998) and why no line of He I is seen. However, the presence of an He II emission line in an H II galaxy is generally associated with a broad He II feature produced by Wolf-Rayet stars (Izotov & Thuan 1998). One may expect to see a narrow He II emission in a galaxy if it is due to the ionization of gas by post-AGB stars (cf. Binette et al. 1994). But in that case, the expected equivalent width of the emission lines would be much smaller than observed in our object and the color of the stellar population would be red, not blue. In our spectra, we see no signature of the presence of old stellar populations like the CN feature ( $\lambda$  4150–4214 Å), or G band ( $\lambda$  4284–4318 Å), or Mg I ( $\lambda$  5156–5196 Å) that are found even in H II galaxies (Raimann et al. 2000). One should note however, that, if this object were an H II galaxy, its metallicity would be extremely low in order to produce such a small [O III]/H $\beta$  ratio, and this could explain why the stellar metallic features would not be seen.



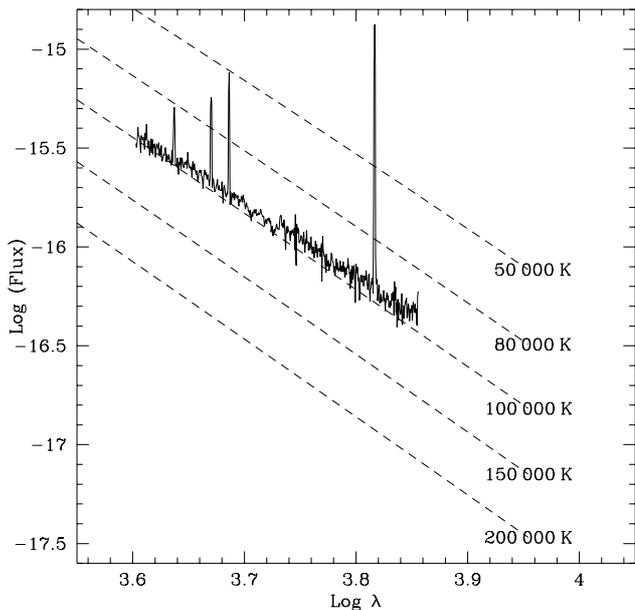
**Fig. 1.** The spectrum of SBS 1150+599A. In the upper panel the single spectrum obtained with a wider slit is presented. In the inset of the upper panel the portion of the summed and averaged spectra is shown to outline the presence of faint lines. In the lower panels the profiles of He II  $\lambda 4686 \text{ \AA}$  and H $\beta$  from the higher resolution spectrum are presented

Perhaps the most compelling argument against SBS 1150+599A being an H II galaxy is the extremely blue nature of the continuum. It is much bluer than the continuum observed in blue compact galaxies (see e.g. Izotov & Thuan 1998 and references therein). Figure 2 shows the observed continuum of SBS 1150+599A in the log Flux – log wavelength plane, with blackbody functions of different temperatures superimposed on it. It clearly indicates that the continuum has a color temperature above 50 000 K. Even active galactic nuclei do not show such a continuum in the the  $\lambda 4000\text{--}7000 \text{ \AA}$  wavelength range (Morris & Ward 1988).

#### 4.4. A halo planetary nebula?

Planetary nebulae are the product of the evolution of post-AGB stars which, after having expelled their outer layers

in stellar winds, become sufficiently hot to ionize their gaseous envelope. While the spectrum of our object is by no means similar to that of a typical planetary nebula, since it shows only one forbidden line between 4000 and 7000  $\text{\AA}$ , we may note that there are examples of planetary nebulae in which the lines that are lacking in the spectrum of SBS 1150+599A are very weak (Aller & Czyzak 1983; Kingsburgh & Barlow 1994). At first sight, our spectra can be interpreted as pertaining to a planetary nebula with a hot exciting star (to produce significant He II emission), that is density bounded (so that no He I, [N II] and [S II] lines are seen), and of very low (or perhaps extremely high) metallicity, so that the [O III]/H $\beta$  ratio is very small, or in very high ionization state. For a PN located in the Galactic halo, one can reasonably eliminate the high metallicity option. Note that observed heliocentric velocity of 190–260  $\text{km s}^{-1}$  (see Table 2) is indeed compatible with SBS 1150+599A belonging to the



**Fig. 2.** The low resolution spectrum of SBS 1150+599A obtained at Cananea observatory is presented in order to show the steepness of the energy distribution in the continuum. Blackbody curves of various temperatures are overplotted for comparison

Galactic halo population (Beers & Sommer-Larsen 1995; Beers et al. 2000).

The observed expansion velocity determined from the  $HWHM$  is  $40 \text{ km s}^{-1}$  (taking a  $FWHM$  of  $2 \text{ \AA}$  and an instrumental width of  $1.5 \text{ \AA}$ ). This is rather high for a PN if one compares with the values listed in the catalogue of expansion velocities of Galactic planetary nebulae by Weinberger (1989) and in the paper by Dopita et al. (1985) on PNe in the Magellanic Clouds, but there are well known PNe which do show similar expansion velocities, for example PNe with [WR] type nuclei (Peña et al. 2001).

In the following section, we further elaborate on the PN hypothesis, with the tools developed for the analysis of this type of objects.

## 5. A model for SBS 1150+599A as a planetary nebula

### 5.1. Photoionization computations

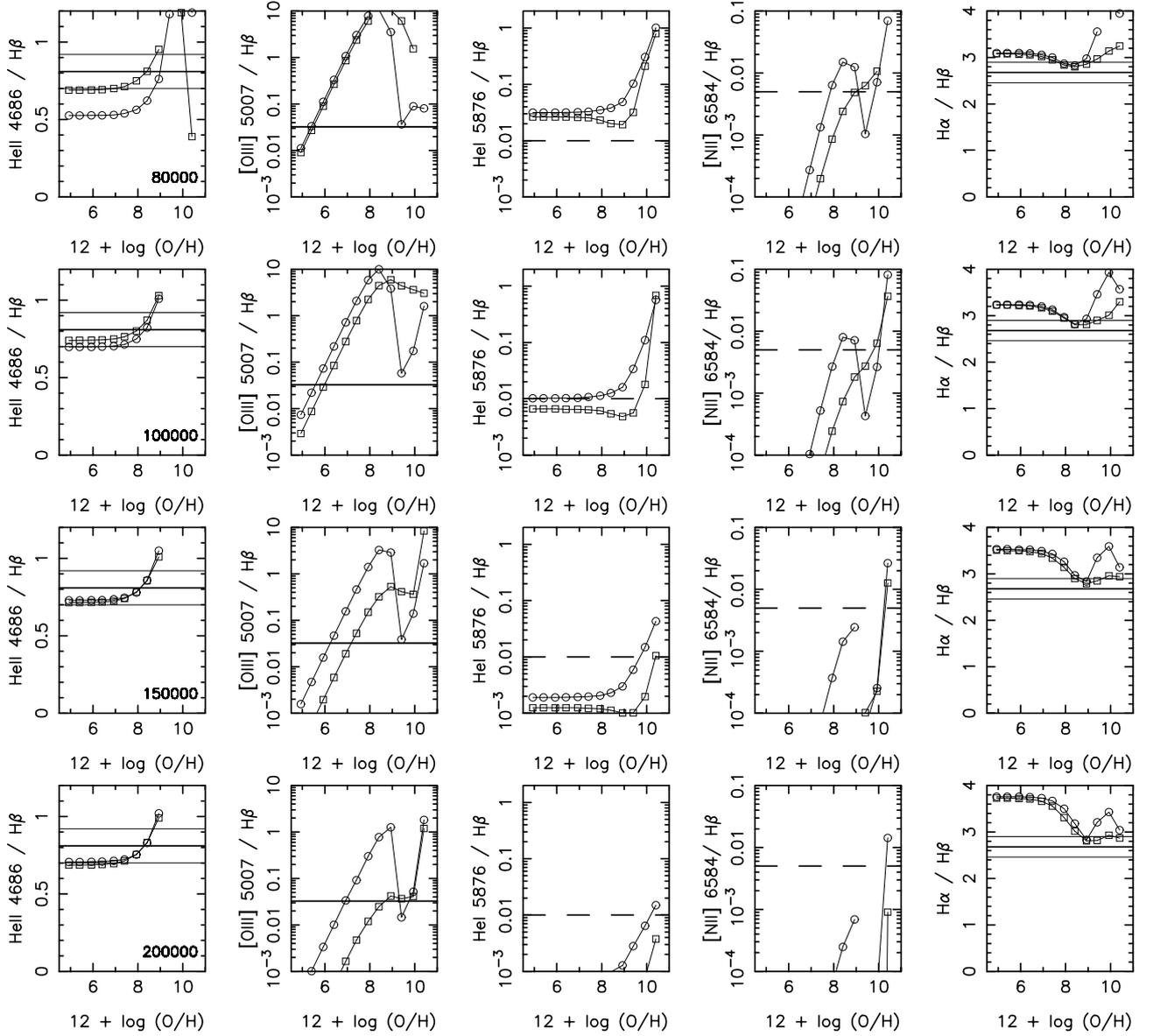
Given the small number of observational constraints, we adopt a very simple model of a planetary nebula which consists of a homogeneous gaseous sphere surrounding a hot star radiating as a blackbody. In order to put some limits on the stellar temperature and oxygen abundances, we construct series of photoionization models in which we specify the stellar temperature,  $T_*$ , the number of photons  $Q$  emitted per second by the star at energies above  $13.6 \text{ eV}$ , the gas density  $n$ , and the filling factor  $\epsilon$  (both assumed constant within the nebula). Each series consists

of 12 models with metallicities ranging from  $10^{-4}$  solar to 30 solar (the high abundance end is shown only for didactic purposes since, as mentioned before, we do not expect a high metallicity object in the halo). Oxygen is the reference element (with the solar abundance in units of  $\log \text{O}/\text{H} + 12$  being taken equal to 8.93 from Anders & Grevesse 1989).

The abundances of the other elements relative to oxygen follow the prescription of McGaugh (1991). Each model is constructed with the photoionization code PHOTO as described in Stasińska & Leitherer (1996). The computations are performed starting from the center and are stopped when the equivalent width of the  $H\beta$  line,  $EW(H\beta)$ , becomes equal to  $130 \text{ \AA}$ . This value takes into account the fact that the spectra do not cover the object completely (we have checked that changing  $EW(H\beta)$  by 50% will not change fundamentally our results). We do not have to consider all possible combinations of  $Q$ ,  $n$  and  $\epsilon$  since for a fixed effective temperature and a given condition imposed on  $EW(H\beta)$ , the nebular ionization structure depends only on  $Q n \epsilon^2$ .

Figure 3 shows the results of our models, computed with  $Q = 3 \cdot 10^{47} \text{ ph s}^{-1}$ , a nebular filling factor  $\epsilon = 0.2$  (values that are typical for planetary nebulae), and two values of  $n$ :  $100 \text{ cm}^{-3}$  (circles) and  $10^4 \text{ cm}^{-3}$  (squares), for different values of  $T_*$ . The first row of panels corresponds to  $T_* = 80 \text{ 000 K}$ , the second to  $100 \text{ 000 K}$ , the third to  $150 \text{ 000 K}$ , and the fourth to  $200 \text{ 000 K}$ . From left to right, the panels show the behavior of  $\text{He II } \lambda 4686 \text{ \AA}/H\beta$ ,  $[\text{O III}] \lambda 5007 \text{ \AA}/H\beta$ ,  $\text{He I } \lambda 5876 \text{ \AA}/H\beta$ ,  $[\text{N II}] \lambda 6584 \text{ \AA}/H\beta$ , and  $H\alpha/H\beta$  as a function of  $\log(\text{O}/\text{H}) + 12$ . The observational constraints are shown by a thick horizontal line if the relevant line is measured (the thin horizontal lines show the error bars) or a dashed line if only an upper limit is available.

All the models show qualitatively a similar behavior. For a given value of  $T_*$ , the effect of increasing the density at a given  $\text{O}/\text{H}$  is to increase the ionization parameter, so that the ratios  $\text{He I } \lambda 5876 \text{ \AA}$ ,  $[\text{N II}]$  and  $[\text{O III}]$  decrease. As  $\text{O}/\text{H}$  increases, cooling becomes more important and the electron temperature drops. This produces an increase in the  $\text{He II } \lambda 4686 \text{ \AA}/H\beta$  and  $\text{He I } \lambda 5876 \text{ \AA}/H\beta$  ratios, due to the temperature dependence of the emissivities of these lines. On the other hand,  $[\text{O III}]/H\beta$  and  $[\text{N II}]/H\beta$  first increase (abundance effect) then decrease (cooling is being gradually shifted from optical to infrared lines). At very high metallicities, these ratios rise again, because the  $[\text{O III}]$  and  $[\text{N II}]$  lines are now mainly produced by recombinations, due to the very low electron temperature. At metallicities less than solar, the values of  $H\alpha/H\beta$  in our models decrease with increasing  $\text{O}/\text{H}$ , while the recombination value (Brocklehurst 1971) would increase. This is due to the fact that, at high electron temperature, collisional excitation contributes to the  $H\alpha$  emission. Clearly, our models show that there is quite a range of input parameters that are compatible with our spectroscopic observational constraints (if one dismisses the  $H\alpha/H\beta$  ratio which poses a problem to which we will come back



**Fig. 3.** Sequences of photoionization models with varying O/H. Each row of panels corresponds to a different value of  $T_*$  as indicated on the leftmost panel. Circles: models with  $n = 100 \text{ cm}^{-3}$ ; squares: models with  $n = 10^4 \text{ cm}^{-3}$ . All of the models are constructed using  $Q = 3 \cdot 10^{47} \text{ ph s}^{-1}$ , and  $\epsilon = 0.2$ , and are density bounded in order to give  $EW(\text{H}\beta) = 130 \text{ \AA}$  (see text). The observed line ratios are indicated by horizontal lines (dashed lines in the case of upper limits, thick continuous lines for measured values, thin lines for the error bars)

below). While models with  $T_* = 80000 \text{ K}$  are not compatible with the lack of detection of  $\text{He I } \lambda 5876 \text{ \AA}$ , models with  $T_*$  between  $100000 \text{ K}$  and  $200000 \text{ K}$  are consistent with the observed constraints in a range of metallicities that depend essentially on the value of the ionization parameter (which, in our parametrization of the problem, is only dependent upon the density). For each value of  $n$ , the value of O/H which matches the observed  $[\text{O III}]/\text{H}\beta$  ratio increases with  $T_*$ , since more and more oxygen ions are found in ionization stages higher than  $\text{O}^{++}$ . At a given  $T_*$ , the solution for O/H increases with  $n$  for the same reason. Clearly, one needs more observational constraints to determine O/H and  $T_*$ .

Note that, as seen in Fig. 2, the observed continuum is compatible with any value of  $T_*$  above  $50000 \text{ K}$  and does not provide additional constraint.

### 5.2. The problem of $\text{H}\alpha/\text{H}\beta$

It is not satisfactory that the ratio produced by the models is much higher than observed. Our computations assume case B. Case A would better apply in the case of our object which is extremely density bounded, but the effect on  $\text{H}\alpha/\text{H}\beta$  would remain virtually unchanged. In our models, collisional excitation of  $\text{H}\alpha$  strongly increases  $\text{H}\alpha/\text{H}\beta$  with respect to the recombination value. In order

to avoid collisional excitation, one needs to lower the electron temperature. This can be achieved by changing the geometry so as to increase the fraction of trace neutral hydrogen and, thus, enhance H Ly $\alpha$  cooling. We have tried to obtain such models, but they required very unrealistic conditions.

Since we are not absolutely certain about the calibration of the H $\alpha$ /H $\beta$  ratio in our spectra, we intend to obtain additional spectroscopy of SBS 1150+599A in order to check the true value of this ratio. We note, however, that in the lists of PNe published by Aller & Keyes (1987) or Kingsburgh & Barlow (1994), there are other planetary nebulae with H $\alpha$ /H $\beta$  ratios similar to the one we find here for SBS 1150+599A. The authors of those papers do not comment on their finding, except to say that in those cases the reddening to the object was considered zero.

Interestingly, in some respects, our object is similar to the one found by Skillman et al. (1989) in the dwarf irregular galaxy Leo A, which shows relatively strong He II  $\lambda$  4686 Å, no detectable [O II]  $\lambda$  3727 Å and no detectable continuum emission and which they interpret as being a PN. Their object shows an H $\alpha$ /H $\beta$  of 2.3, which they tentatively attribute to scattering by dust near the PN.

There are astrophysical objects (old novae, cataclysmic variables, Be stars) where the H $\alpha$ /H $\beta$  is notoriously far below the recombination value, reaching values of the order of one. However, the conditions invoked to explain the flat observed Balmer decrements, local thermal equilibrium (Williams 1980) or stimulated emission by a strong radiation field (Elitzur et al. 1983; Williams & Shipman 1988) require a high density, which is excluded in the case of our object, since it shows the forbidden line of [O III].

### 5.3. Distance and structural properties of SBS 1150+599A

We now make use of other properties of SBS 1150+599A, to further constrain the models. From the observed angular radius and H $\beta$  flux (assuming that interstellar extinction is negligible, which is likely from the observed value of H $\alpha$ /H $\beta$  and from the high Galactic latitude of the object) we can compute the distance of the object assuming a certain mass and filling factor of the gas emitting in H $\beta$ . Since our object is density bounded, such a procedure (the Shklovsky method) provides a reasonable estimate of the true distance to the object. We have

$$d = 0.14 F_{\text{H}\beta}^{-0.2} \theta^{-0.6} M_{\text{neb}}^{0.4} \epsilon^{-0.2}$$

where  $d$  is the distance in kpc,  $F_{\text{H}\beta}$  is the H $\beta$  flux in  $\text{erg cm}^{-2} \text{s}^{-1}$ ,  $\theta$  is the angular radius in arcsec and  $M_{\text{neb}}$  is the nebular mass in solar masses. We adopt an angular radius of  $5''$ , corresponding to the spatial extension of the emission lines in our spectra and a total H $\beta$  flux  $F_{\text{H}\beta} = 2.4 \cdot 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$ , assuming that the nebula is round.

Taking  $M_{\text{neb}} = 0.2 M_{\odot}$  and  $\epsilon = 0.2$  gives  $d = 20.4 \text{ kpc}$  which is within acceptable distances for a halo object

**Table 3.** Derivation of the structural parameters of SBS 1150+599A

$M_{\text{neb}} [M_{\odot}]$	0.2	0.2	0.1
$\epsilon$	1	0.2	0.2
$d$ [kpc]	14.8	20.4	15.5
$R_{\text{neb}}$ [pc]	.36	.50	.40
$n$ [ $\text{cm}^{-3}$ ]	30	59	57
$t_{\text{exp}}$ [yr]	9100	12 500	10 000
$T_*$ [K]	$Q^a$	$Q$	$Q$
$\log \text{O/H} + 12$	$M_*(Q)^b$	$M_*(Q)$	$M_*(Q)$
	$M_*(T_*)^b$	$M_*(T_*)$	$M_*(T_*)$
100 000	625	1220	593
5.8	–	–	–
	58.5	57.5	.58
150 000	1450	2850	1370
6.2	.59	.57	.59
	.70	.58	.59
200 000	2530	4980	2400
7.	.585	–	.58
	–	–	–

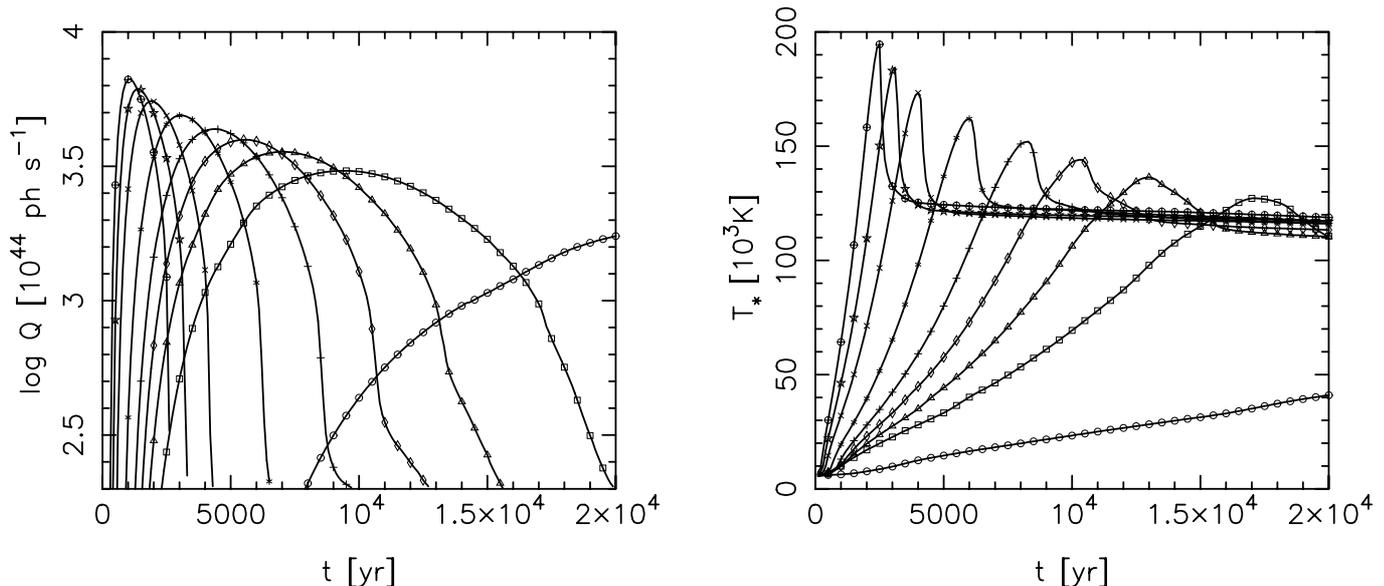
<sup>a</sup> In  $10^{44} \text{ ph s}^{-1}$ .

<sup>b</sup> In  $M_{\odot}$ .

(Zaritsky 1999). Taking  $M_{\text{neb}} = 0.1 M_{\odot}$  rather than  $0.2 M_{\odot}$  gives  $d = 15.5 \text{ kpc}$ , taking  $\epsilon = 1$  rather than  $0.2$  gives  $d = 14.8 \text{ kpc}$ .

Adopting as a working hypothesis the values  $M_{\text{neb}} = 0.2 M_{\odot}$  and  $\epsilon = 0.2$ , we obtain a nebular radius  $R_{\text{neb}}$  of  $0.5 \text{ pc}$  and a gas density of  $60 \text{ cm}^{-3}$ . The values of  $R_{\text{neb}}$  and  $n$  obtained using various combinations of  $M_{\text{neb}}$  and  $\epsilon$ , are reported in Table 3.

It is easily shown that, for a star of given  $T_*$ , the observed  $EW(\text{H}\beta)$  can be obtained by a whole family of models sharing the same value of  $(M_{\text{neb}}n/Q)$  (for a given electron temperature). From the models we have computed, and which return the value of  $M_{\text{neb}}$  that corresponds to  $EW(\text{H}\beta) = 130 \text{ \AA}$ , we can readily infer the value of  $Q$  that corresponds to a chosen  $M_{\text{neb}}$ . These values, which produce acceptable models, are reported in Table 3, for different choices of  $T_*$ . One sees that the values of  $Q$  are all within a factor 5 of the input value in our models presented in Fig. 3. The densities reported in Table 3 for SBS 1150+599A are of the order of  $50 \text{ cm}^{-3}$ . Therefore, of the series of models presented in Fig. 3, those with  $n = 10^4 \text{ cm}^{-3}$  are not relevant for our object but those with  $n = 100 \text{ cm}^{-3}$  have an ionization parameter roughly compatible with the results from Table 3. We can then infer an approximate oxygen abundance for SBS 1150+599A by finding where the sequences represented by circles meet the observed value of [O III]  $\lambda$  5007 Å/H $\beta$  in Fig. 3. These abundances are reported in Table 3 below the corresponding  $T_*$ . The accepted values still span a large range, but oxygen abundances over one fiftieth of solar are clearly eliminated. This makes of SBS 1150+599A by far the most oxygen-poor PN known.



**Fig. 4.** The values of  $Q$  and  $T_*$  as a function of time interpolated from the grid of post-AGB tracks by Blöcker (1995) for central star masses from  $0.56$  to  $0.64 M_{\odot}$  by intervals of  $0.01 M_{\odot}$ . The evolution is the slowest for the lowest stellar masses

By using a grid of stellar evolution tracks for post-AGB stars (we use the one computed by Blöcker (1995) for hydrogen burning PN nuclei), it is possible to go one step further, if one assumes that the transition time between the PN ejection and the beginning of the evolution of the nucleus off the AGB is zero. We first estimate the expansion time, from the formula  $t_{\text{exp}} = R_{\text{neb}}/v_{\text{exp}}$ . The derived number depends on the assumptions on  $M_{\text{neb}}$  and  $\epsilon$  (see Table 3), but is always around  $10\,000$  yr. Then, from Fig. 4, which has been obtained by interpolating the grid of Blöcker (1995) on a finer grid in star masses, we derive  $M_*(Q)$  and  $M_*(T_*)$ , the values of the PN nuclei masses that correspond to  $Q$  and  $T_*$  respectively. These values are reported in Table 3. If the central star evolved exactly as predicted by Blöcker (1995) and if SBS 1150+599A were perfectly represented by our toy model, the true central star mass would be obtained for the value of  $T_*$  which makes  $M_*(Q)$  and  $M_*(T_*)$  equal. From an inspection of Table 3, one finds for the central star of SBS 1150+599A a temperature of  $\sim 150\,000$  K and a mass of  $\sim 0.58$ – $0.59 M_{\odot}$ .

These numbers are not to be taken too literally, of course. Our model is extremely simplistic. Hydrodynamical computations (Bobrowsky & Zipoy 1989; Mellema 1994) have warned against a blind use of expansion times and we know that PNe are seldom spherical with a uniform density. Besides, it has been shown empirically by studying samples of planetary nebulae in various galaxies, that the central stars of planetary nebulae evolve differently according to the galactic context (Stasińska et al. 1998; Dopita et al. 1997).

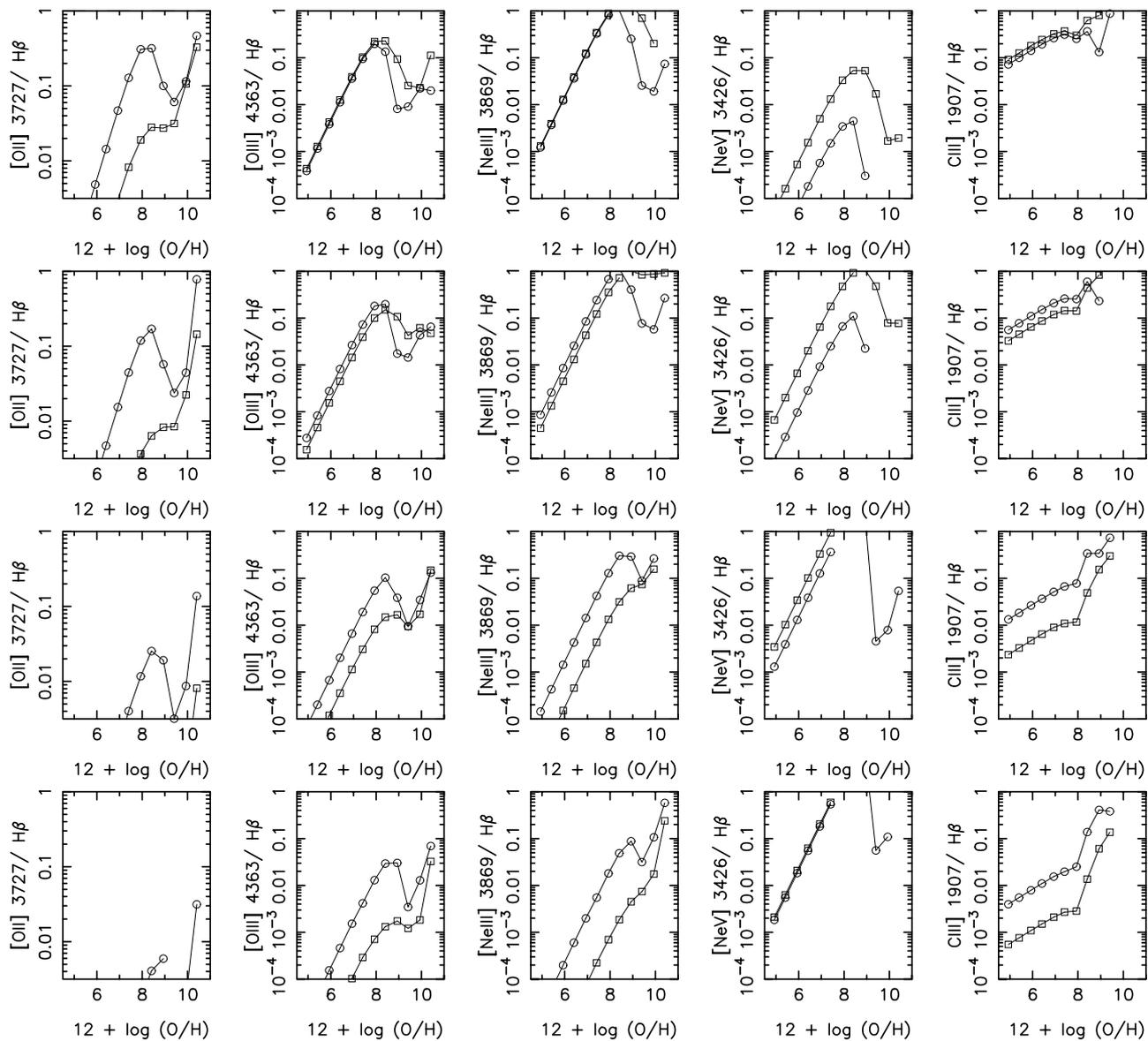
Nevertheless, the fact that, with our simple approach, we are able to give a reasonable picture of SBS 1150+599A is extremely encouraging. As a consequence, we favor for SBS 1150+599A an oxygen abundance of  $\log O/H+12 \sim 5.8$ – $6.8$ .

#### 5.4. The helium abundance in SBS 1150+599A

The observed  $\text{He II } \lambda 4686 \text{ \AA}/H\beta$  leads to a  $\text{He}^{++}/H$  ratio of  $0.072 \pm 0.010$ . The observed limit on  $\text{He I } \lambda 5876 \text{ \AA}$  leads to  $\text{He}^+/H < 0.009$ . Unfortunately, due to the quality of our data, these estimates are not sufficiently accurate to provide any useful indication of the primordial helium abundance. The only thing which can be said at this stage is that the helium abundance we are finding is consistent with our interpretation that SBS 1150+599A is an extremely oxygen poor PN.

#### 5.5. Need for further observations

One way to better constrain the oxygen abundance (and to test the hypothesis of mixing, see Sect. 6) in SBS 1150+599A would be through deeper spectroscopy in the optical, which should reveal the weak  $[\text{Ne III}] \lambda 3869 \text{ \AA}$ ,  $[\text{Ne V}] \lambda 3426 \text{ \AA}$  lines, and possibly also the lines from the low excitation e.g.,  $[\text{O II}] \lambda 3727 \text{ \AA}$ ,  $[\text{N II}] \lambda 6584 \text{ \AA}$ . Our models show that even the  $[\text{O III}] \lambda 4363 \text{ \AA}$  line could be measurable. This would considerably improve the quality of the oxygen abundance determination. Ultraviolet spectra would bear important information. For example, they would place limits on the carbon abundance and on the ionization structure of the nebula through the  $[\text{O IV}] \lambda 1394 \text{ \AA}$  line. These lines are expected to be measurable, despite the low metallicity of the object, due to the high electron temperature which boosts the collisionally excited ultraviolet lines with respect to the optical ones. A direct observational constraint on the nebular density would be very valuable too. The optical doublets which are used for that ( $[\text{S II}] \lambda 6716, 6731 \text{ \AA}$  and  $[\text{Ar IV}] \lambda 4711, 4740 \text{ \AA}$ ) would be probably too weak to be measured, but one may hope to measure the  $[\text{C III}] \lambda 1907, 1909 \text{ \AA}$  doublet in the ultraviolet.



**Fig. 5.** Predicted values of some line ratios for the same models as shown in Fig. 3

We show in Fig. 5 the predicted intensities relative to  $H\beta$  of some important lines, for the same models as in Fig. 3. These predictions are purely indicative and are given only to estimate the feasibility of future observations. For example the intensity of  $[\text{Ne v}]\lambda 3426 \text{ \AA}$  strongly depends on the assumed spectral energy distribution (here a simple blackbody was used). That of  $[\text{C III}]\lambda 1907, 1909 \text{ \AA}$  is probably larger than shown here since C/O ratios in PNe tend to be larger (Henry et al. 2000) than given by the prescription of Mc Gaugh (1991) used in these exploratory models.

## 6. Discussion

Our main conclusion is that, most probably, SBS 1150+599A is a halo planetary nebula. With the nomenclature of the Strasbourg-ESO catalogue of planetary nebulae (Acker et al. 1992) it becomes PN

G135.9+55.9. Our analysis favors an oxygen abundance lower than 1/100 and probably around 1/500 of solar. This would make it the most oxygen-poor PN known so far. Among the dozen of known Galactic halo PNe (Conlon et al. 1993; Napiwotzki et al. 1994; Howard et al. 1997 and references therein; Jacoby et al. 1997), the most oxygen-poor is K 648 with a  $\log \text{O/H} + 12$  estimated at 7.61.

How does this fit with our knowledge of the formation and evolution of planetary nebulae and on the evolution of the Galactic halo?

It is obviously not surprising to find a low metallicity object in the halo, hundreds of stars have been discovered with metallicities (as referred to the iron abundance)  $[\text{Fe/H}] < -2$  dex, the lowest ones reaching  $-4$  dex (see e.g. references in Beers 1999; Norris 1999). Oxygen abundances, however, have been determined in only a fraction of these metal-poor stars (Laird 1999). The lowest

oxygen abundances measured in stars are around 1/200 solar (Boesgaard et al. 1999; Israelian et al. 2001). It should be remembered, though, that oxygen abundance measurements in halo stars are difficult and uncertain (see the discussion by McWilliam 1997; Hill 2001 and the papers edited by Barbuy 2001). Our determination of the oxygen abundance in SBS 1150+599A is not very accurate either, and it would be important to constrain it better with appropriate observations. Indeed, if the oxygen abundance in SBS 1150+599A reflects the oxygen content of the material out of which the progenitor star was formed, as is expected from theoretical models of AGB stars (Forestini & Charbonnel 1997), a proper determination of this abundance would give interesting clues to the understanding of the formation of the Galactic halo and of the first stars.

There is, however, the possibility that the oxygen abundance in SBS 1150+599A has been modified from the pristine oxygen abundance by mixing processes in the progenitor star. Indeed, differences in abundance ratios from star to star in globular clusters giants seem to indicate that in those stars deep mixing has brought to the surface the products of proton capture in the hydrogen burning shell. (Ivans et al. 1999; Weiss et al. 2000 and references therein) However, this is not seen in field stars (Gratton et al. 2000; Charbonnel & Palacios 2001). Usually, abundance ratios observed in PNe do not indicate that oxygen has been depleted in the progenitor by mixing (Richer et al. 1998). There is however the case of the halo planetary nebula BB-1 which shows a Ne/O ratio much higher than the remaining planetary nebulae (Howard et al. 1997 and references therein), and for which destruction of  $^{16}\text{O}$  in the ON cycle has been suggested.

If the progenitor of SBS 1150+599A was indeed one of the most metal poor objects known in the galaxy, could it have produced a planetary nebula that we see now? With such a low metallicity, the star must be older than the most metal-poor globular clusters, i.e. about 14 Myr (VandenBerg 1999) and from stellar evolution models (Charbonnel et al. 1999) we derive that the initial stellar mass would be 0.8–1.0  $M_{\odot}$ . If we adopt the initial-final mass relation of Weideman (1987) or even that of Richer et al. (1997), the mass of the planetary nebula nucleus would be around 0.55–0.555  $M_{\odot}$ . According to the post-AGB stellar evolution models of Blöcker (1995 and references therein), the evolution of the star off the AGB would be so slow that the ejected material would have been totally dispersed before being ionized. There are however several possibilities to reconcile the low metallicity of the object and the fact that it has produced a planetary nebula visible now. First, the star could have been formed from infalling material, according to a scenario discussed by Carney (1999). Then its age would be smaller than that derived for the bulk of metal poor globular clusters, and its mass larger than 1  $M_{\odot}$ . Second, there are many uncertainties in the derivation of the initial-final mass relation (Weideman 1987; Bragaglia et al. 1995; Richer et al. 1997) and it is possible that at low metallicities the final mass would be larger, for example due to decreased mass loss.

One cannot exclude some intrinsic scatter in the initial-final mass relation, for example due to close binary stellar evolution. Third, the stellar post-AGB evolution itself can be questioned. For example, Kato & Hachisu (1993) argue that computations using OPAL opacities drastically shorten the evolutionary time scale.

For all of these reasons, then, our interpretation that SBS 1150+599A is an extremely oxygen-poor halo PN does make sense. Conversely, a more detailed study of this object would provide valuable constraints on the evolution intermediate mass stars of low metallicity and on the chemical evolution of the galaxy.

Is SBS 1150+599A unique? If we take a total enclosed mass for our Galaxy (within 200 kpc) of  $1.4 \cdot 10^{12} M_{\odot}$ , a mass to light ratio of 100 in solar units (Zaritsky 1999), and if we adopt a PN production rate of  $50 \cdot 10^{-8} \text{ PN}/L_{\odot}$  (Ciardullo 1995), we arrive to a total of 7000 PNe in the Galaxy. From the observed metallicity distribution of metal poor stars (Norris 1999), one does not expect to find a large number of such objects in the Galactic halo. However, the criteria for discovering PNe in objective prism or imaging surveys are based on the strength of the [O III] line. SBS 1150+599A was probably first discarded as a planetary nebula because of its very weak [O III] line and because of the absence of other emission lines usually seen in planetary nebulae. In this respect, it might prove rewarding to reexamine the spectra of the objects declared as cataclysmic variables or emission line stars in objective prism surveys.

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## References

- Acker, A., et al. 1992, The Strasbourg-ESO catalogue of Galactic Planetary Nebulae
- Aguilar, L., Hut, P., & Ostriker, J. 1988, ApJ, 335, 720
- Allen, D. A. 1984, Proc. Astron. Soc. Aust., 5, 369
- Aller, L. H., & Czyzak, S. J. 1983, ApJS, 51, 211
- Aller, L. H., & Keyes, C. D. 1987, ApJS, 65, 405
- Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 97
- Balayan, S. K. 1997, Afz, 40, 101
- Barbuy, B., (eds.) 2001, Oxygen Abundances in Old Stars and Implications to Nucleosynthesis and Cosmology, IAU 24 General Assembly, in press
- Beers, T. C., & Sommer-Larsen, J. 1995, ApJS, 96, 175
- Beers, T. C. 1999, in ASP Conf. Ser. 165, The Galactic Halo, ed. B. K. Gibson, T. S. Axelrod, & M. E. Putman, 202
- Beers, T. C., Chiba, M., Yoshii, Y., et al. 2000, AJ, 119, 2866
- Bełczyński, K., Mikołajewska, J., Munari, U., Ivison, R. J., & Friedjung, M. 2000, A&AS, 146, 407

- van den Bergh, S. 1999, *A&AR*, 9, 273
- Bicay, M. D., Stepanian, J. A., Chavushyan, V. H., et al. 2000, *A&AS*, 147, 169
- Binette, L., Magris, C. G., Stasińska, G., & Bruzual, A. G. 1994, *A&A*, 292, 13B
- Blöcker 1995, *A&A*, 299, 755
- Bobrowsky, M., & Zipoy, D. M. 1989, *ApJ*, 347, 307
- Boesgaard, A. M., King, J. R., Deliyannis, C. P., & Vogt, S. S. 1999, *AJ*, 117, 492
- Bragaglia, A., Renzini, A., & Bergeron, P. 1995, *ApJ*, 443, 735
- Brocklehurst, M. 1971, *MNRAS*, 153, 471
- Carney, B. W. 1999, in *ASP. Conf. Ser. 165, The Galactic Halo*, ed. B. K. Gibson, T. S. Axelrod, & M. E. Putman, 230
- Carrasco, L., Tovmassian, H. M., Stepanian, J. S., et al. 1998, *AJ*, 115
- Charbonnel, C., Däppen, W., Schaerer, D., et al. 1999, *A&AS*, 135, 405
- Charbonnel, C., & Palacios, A. 2001, in *The evolution of galaxies. I. Observational clues*, ed. J. Vilchez, G. Stasińska, & E. Perez (Kluwer), in press
- Ciardullo, R. 1995, in *IAU Highlights of Astronomy 10* (1st ed; Dordrecht: Kluwer), 507
- Conlon, E. S., Dufton, P. L., McCausland, R. J. H., & Keenan, F. P. 1993, *ApJ*, 408, 593
- Dopita, M. A., Lawrence, C. J., Ford, H. C., & Webster, B. L. 1985, *ApJ*, 296, 390
- Dopita, M. A., Vassiliadis, E., Wood, P. R., et al. 1997, *ApJ*, 474, 188
- Drabek, S. V., Kopilov, I. M., Somov, N. N., & Somova, T. A. 1985, *Astrofiz. Issled. (Izv. SAO.)*, 22, 64
- Elitzur, M., Ferland, G. J., Mathews, W. G., & Shields, G. A. 1983, *ApJ*, 272, L55
- Forestini, M., & Charbonnel, C. 1997, *A&A*, 123, 241
- Gratton, R. G., Sneden, C., Carretta, E., & Bragaglia, A. 2000, *A&A*, 354, 169
- Garnavich, P. 1999, *JAAVSO*, 27, 79
- Henry, R. B. C., Kwitter, K. B., & Bates, J. A. 2000, *ApJ*, 531, 928
- Hill, V. 2001, in *The evolution of galaxies. I. Observational clues*, ed. J. Vilchez, G. Stasińska, & E. Perez (Kluwer), in press
- Howard, J. W., Henry, R. B. C., & McCartney, S. 1997, *MNRAS*, 284, 465
- Israelian, G., Rebolo, R., Garcia Lopez, R. J., et al. 2001 [*astro-ph 0101032*]
- Ivans, I. I., Sneden, C., Kraft, R. P., et al. 1999, *AJ*, 118, 1273
- Iverson, R. J., Bode, M. F., & Meaburn, J. 1994, *A&AS*, 103, 201
- Izotov, Y. I., & Thuan, T. X. 1998, *ApJ*, 500, 188
- Jacoby, G. H., Morse, J. A., Fullton, L. K., Kwitter, K. B., & Henry, R. B. C. 1997, *AJ*, 114, 2611
- Kato, M., & Hachisu, I. 1993, in *Symp. IAU 155, Planetary Nebulae*, ed. R. Weinberger, & A. Acker (Kluwer), 367
- Kenyon, S. J. 1986, *The Symbiotic Stars* (Cambridge Univ. Press, Cambridge)
- Kingsburgh, R. L., & Barlow, M. J. 1994, *MNRAS*, 271, 257
- Leitherer, C., & Heckman, T. M. 1995, *ApJS*, 96, 9
- Laird, J. B. 1999, in *ASP. Conf. Ser. 165, The Galactic Halo*, ed. B. K. Gibson, T. S. Axelrod, & M. E. Putman, 248
- Markarian, B. E., & Stepanian, D. A. 1983, *Afz*, 19, 639
- Markarian, B. E., Stepanian, J. A., & Erastova, L. K. 1987, in *IAUS, No. 121, Observational Evidence of Activity in Galaxies*, ed. E. E. Khachikian, K. J. Fricke, & J. Melnick, 25
- Mc Gaugh, S. S. 1991, *ApJ*, 380, 140
- Mellema, G. 1994, *A&A*, 290, 915
- McWilliam, A. 1997, *ARA&A*, 35, 503
- Morris, S. L., & Ward, M. J. 1988, *MNRAS*, 230, 639
- Napiwotzki, R., Heber, U., & Köppen, J. 1994, *A&A*, 292, 239
- Norris, J. E. 1999, in *ASP. Conf. Ser. 165, The Galactic Halo*, ed. B. K. Gibson, T. S. Axelrod, & M. E. Putman, 213
- Peña, M., Stasińska, G., & Medina, S. 2001, *A&A*, in press
- Raimann, D., Bica, E., Storch-Bergmann, T., Melnick, J., & Schmitt, H. 2000, *MNRAS*, 314, 295
- Richer, M. G., McCall, M. L., & Arimoto, N. 1997, *A&AS*, 122, 215
- Richer, M. G., McCall, M. L., & Stasińska, G. 1998, *A&A*, 340, 67; 1997, *A&AS*, 122, 215
- Salzer, J. J., MacAlpine, G. M., & Boronson, T. A. 1989, *ApJS*, 70, 479
- Schwobe, A. D., Mantel, K.-H., & Horne, K. 1997, *A&A*, 319, 894
- Skillman, E. D., Kennicutt, R. C., & Hodge, P. W. 1989, *ApJ*, 347, 875
- Stasińska, G., & Leitherer, C. 1996, *ApJS*, 107, 661
- Stasińska, G., Richer, M. G., & McCall, M. L. 1998, *A&A*, 336, 667
- Stepanian, J. A. 1994, *D. Sci. Thesis, Nizhnij Arkhys*
- Stepanian, J. A. 1994b, in *IAUS, No. 161, Astronomy from Wide-Field Imaging*, ed. H. T. MacGillivray et al., 731
- Stepanian, J. A., Chavushyan, V. H., Carrasco, L., Tovmassian, H. M., & Erastova, L. K. 1999, *PASP*, 111, 1099
- VandenBerg, D. A. 1999, in *ASP. Conf. Ser. 165, The Galactic Halo*, ed. B. K. Gibson, T. S. Axelrod, & M. E. Putman, 46
- Warner, B. 1995, *Cataclysmic Variables* (Cambridge Univ. Press, Cambridge)
- Weideman, V. 1987, *A&A*, 188, 74
- Weinberger, R. 1989, *A&AS*, 78, 301
- Weiss, A., Denissenkov, P. A., & Charbonnel, C. 2000, *A&A*, 356, 181
- Williams, R. E. 1980, *ApJ*, 235, 939
- Williams, G. A., & Shipman, H. L. 1988, *ApJ*, 326, 738
- Zaritsky, D. 1999, in *ASP. Conf. Ser. 165, The Galactic Halo*, ed. B. K. Gibson, T. S. Axelrod, & M. E. Putman, 34
- Zickgraf, F.-J., Thiering, I., Krautter, J., et al. 1997, *A&AS*, 123, 103