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Hβ Fluxes from Planetary Nebulae

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Abstract We present new measurements of $H\beta$-fluxes for 13 planetary nebulae. Including in our sample are five objects with no flux hitherto measured probably belonging to the galactic bulge. The VLA fluxes at 5 GHz combined with our data allowed an evaluation of the color excess for those planetaries. Magnitudes at 4819 Å and the Zanstra temperatures are also derived for the central stars of some of the observed nebulae.

1. INTRODUCTION

It was shown by Zanstra[1] that the observed recombination Balmer line fluxes from planetary nebulae could be a measure of the Lyman continuum emission from the central stars, provided that the nebulae be optically thick to such an ionizing radiation. Therefore, if this condition is satisfied, the temperature of the central starcan be derived if we also measure the continuum flux from the star itself at any other wavelength and we assume a blackbody spectrum.

On the other hand, if we combine the $H\beta$ and the radiofluxes of the nebula, the interstellar extinction associated with the object can be evaluated. The proper reddening correction is applied to the observed line intensity ratios, after which we obtain the physicalconditions inside the nebula and its chemical composition. If a statistical relation between reddening and distance is known from measurements of nearby stars, it is also possible to estimate reliable distances to the nebulae.

In the present work we present $H\beta$ flux measurements for 13 planetary nebulae observed at the Brazilian Astrophysical Observatory (OAB). For some objects it was possible to estimate the magnitudes of the central stars and consequently to evaluate the Zanstra temperature. The reddening has been estimated for all the nebulae with available VLA fluxes at 5 GHz. For most of them it was possible to compare our reddening estimates with those obtained by other methods. Five objects in our sample are suspect to be localized inside the bulge of our Galaxy for which no other reddening estimates were available.

In the next sections we present our observations and we discuss our main results.

2. THE OBSERVATIONS

In our first run, seven planetaries were observed with the 1.6m telescope. A single-channel photometer controlled by a microcomputer was used in these observations with two Schott filters centered at λ4861Å whose characteristics are given in Table 1. The data obtained with both filters were combined conveniently in order to subtract the underlying continuum due to the star and the nebula itself.

Table 1 - Filter Characteristics

FILTER	DIAMETER	CENTRAL WAVELENGTH (A)	BANDWIDTH (A)
Schott 1	9 mm	4861	15.2
Schott 2	9 mm	4861	54.5
São Carlos 1	30 mm	4863	28.5
São Carlos 2	30 mm	4819	32.3

Other six planetaries were observed with the 0.6m Zeiss reflector using the same single-channel photometer but with another set of interferential filters prepared for us by the Instituto de Física e Química de São Carlos (University of São Paulo). The characteristics of these filters are also given in Table 1. The larger diameter of these filters allows us to measure $H\beta$ fluxes from nebulae with angular dimensions as large as 2'.2.

Our photometric system was calibrated through the observations of planetaries with known $H\beta$-fluxes. Those objects used for calibration in both telescopes are listed in Table 2. When more than one reference is given, the adopted flux is the simple average of all the values. For the continuum fluxes we have used the results by Kohoutek and Martin[2], interpolating their values in order to obtain the

the possibility that the different magnitude values derived by both groups at different epochs are real, new observations of this object are necessary to verify the existence or not of such a variability.

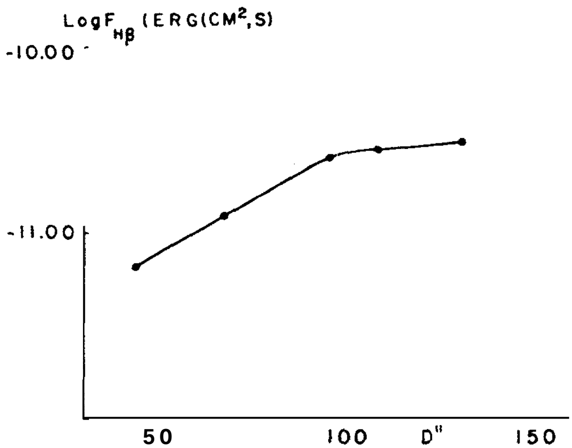

Fig.1 - The logarithm of the observed Hβ-flux as a function of the aperture diaphragm diameter in seconds of arc.

Inspection of Table 4 reveals the very well known fact that in general $T_z(HeII) > T_z(HI)$. The rather large difference between both temperatures for NGC 2792 should probably be attributed to the fact that the nebula is not optically thick to the H-ionizing radiation. However it is worth to mention that Cahn[3] considers that nebula as being optically thick to the Lyman continuum radiation. He adopts different values for the stellar and *H*β fluxes but even with his figures the hydrogen Zanstra temperature is rather low. An alternative explanation may be related to the existence of an expanding atmosphere, strongly supported by the observation of P-Cyg profiles in *UV* lines from many planetaries. If a certain amount of the 4686 radiation is formed in such a wind, we are certainly overestimating the amount of the radiation shortward of 2288 and consequently, the *HeII* Zanstra temperature.

In the case of NGC 5189 a reliable distance has been recently derived by Gathier[11]. Based on his data, one can conclude that with a nebular radius of about 0.6 pc and an unusually high ionized mass of about 2.9 $M_\odot$, the nebula is probably partially transparent to the H -ionizing radiation. As a consequence, the H- Zanstra temperature flux at the effective wavelength of our filter.

Table 2 - Standard Objects

OBJECTS	log $F_{H\beta}$(erg cm^{-2} s^{-1})	TELESCOPE	REFERENCES
N6818	- 10.50	1.62m	(2), (3)
N7009	- 9.78	"	(5)
N1535	- 10.39	"	(3), (4), (5)
J320	- 11.39	"	(3), (4), (5)
IC418	- 9.59	"	(3), (2), (4), (5), (6)
N2022	- 11.10	"	(2)
IC2165	- 10.89	"	(2), (4)
N3211	- 11.06	0.60m	(2)
N3918	- 10.04	"	"
N5315	- 10.42	"	"
N5882	- 10.38	"	"
N6326	- 11.09	"	"
N6565	- 11.21	"	"
N6572	- 9.81	"	"
N6629	- 10.97		"

References: (2) Kohoutek & Martin (1981); (3) Cahn (1984); (4) Carrasco et *al.* (1983); (5) Pottasch (1984); (6) Pacheco et *al.* (1985).

The measurements were reduced through standard photometric techniques with the atmospheric extinction being evaluated each night.

Table 3 shows the results for our programme objects. The first columns identifies the nebula and the second gives the logarithm of the flux in erg cm^{-2} s^{-1}. Typical errors are of the order of 0.02 in log $F_{H\beta}$. The third column gives the number of independent measurements, the fourth the date of the observing mission and the fifth gives the telescope used.

Table 3 · Programme Objects

OBJECTS	log $F_{H\beta}$ (erg cm^{-2} s^{-1})	n	DATE	TELESCOPE
PK-2-3.3	- 12.07	1	(a)	1.62m
PK 2-3.5	- 11.96	1	(a)	1.62m
PK 2-4.1	- 11.93	1	(a)	1.62m
PK 6-3.3	- 12.11	1	(a)	1.62m
PK 6+8.1	- 12.01	1	(a)	1.62m
PK108-76.1	- 12.48	1	(a)	1.62m
N2346	- 11.24	2	(a)	1.62m
N2440	- 10.45	9	(b)	0.60m
N2452	- 11.55	7	(b)	0.60m
N2792	- 11.44	7	(b)	0.60m
N2867	- 10.57	5	(b)	0.60m
N5189	- 10.52	3	(b)	0.60m
PK320-28.1	- 11.48	1	(b)	0.60m

(a) 17/18 September 1982; (b) 29/May to 3/June 1984

3. MAGNITUDES AND ZANSTRA TEMPERATURES

The São Carlos filters used at the 0.6m telescope allowed a trustful evaluation of the continuum flux at λ4819Å, allowing one to estimate the magnitude of the central star at this wavelength. A detailed analysis of the correction due to the nebular continuum emission will be given in a future paper Pacheco *et al.*[6], where Scanner data recently obtained from central stars of planetaries will be presented.

Under the assumption that the star radiates like a blackbody the geometrical dilution factor can be written as a function of the resulting continuum flux of the stellar radiation at λ4819Å.

$$\left(\frac{R}{D}\right)^2 = \frac{F_{\lambda 4819}}{\pi B(T)_{\lambda 4819}} \qquad (1)$$

where R is the stellar radius, D is the distance and T is theeffective stellar temperature.

If the nebula is optically thick to the ionizing radiation we can equate the rate of photons emitted by the star, shortward of the Lyman limit (ν_L), to the total rate of recombinations (excepting the ground level) inside the nebula, namely,

$$4\pi \; R^2 \int_{\nu_L}^{\infty} \frac{\pi B_\nu (T)}{h\nu} \, d\nu = \alpha_B (HI, T_e) \int n_e n_p dV \qquad (2)$$

where $\alpha_B (HI, T_e)$ is the total recombination rate for hydrogen excepting the fundamental level, T_e is the eletronic temperature and n_e, n_p are the electron and the proton densities respectively.

The observed HB flux from the nebula is

$$F_{H\beta} = \frac{1}{4\pi D^2} \alpha_{H\beta} (T_e) \, h\nu_\beta \int n_e n_p dV \qquad (3)$$

where $a_{H\beta}(T_e)$ is the effective recombination coefficient for Hβ emission Brocklehurst [7].

From equations (1), (2) and (3) one obtain

$$\frac{G(T)}{\pi B(T)_{\lambda 4819}} = \frac{F_{H\beta}}{h\nu_\beta F_{\lambda 4819}} \cdot \frac{\alpha_B (HI, T_e)}{\alpha_{H\beta}(T_e)} \qquad (4)$$

where we have defined

$$G(T) = \int_{\nu_L}^{\infty} \frac{\pi B_\nu (T)}{h\nu} \, d\nu \qquad (5)$$

The first member of equation (4) is a function of the star's temperature only, while the second member depends on the observed quantities and on the ratio oftwo recombination coefficients, which has a weak dependence on the electron temperature. A similar equation can be derived for the ionized helium recombination lines, using the rate of ionizing photons shortwards 2288 and adequate recombination coef- ficients. The temperatures derived from these ions are then known re- spectively as the H and *HeII* Zanstra temperatures.

Our results are shown in Table 4. The second column gives the resulting star magnitudes at 4819 (not corrected for reddening) and the other colums the derived Zanstra temperatures. The line intensity ratio $I_{\lambda 4686}$ $(HeII)/I_{H\beta}$ and the reievant electron temperatures were taken from Kaler[8] and Pott:asch[S].

Table 4

OBJECT	··4819	$T_z(HI$	$T_z(HeII)$
N2792	15.40	43900	88350
N2867	15.05	73500	99600
N5189	15.10	77300	108000
PK320-28.1	15.14	40000	-

For NGC 2440 our observed continuum flux is entirely consistent with the lower limit for the magnitude of the central star V > 16 derived recently by Reay et *al.*[9] . For NGC 2792 Cahn[3] gives a magnitude B=14.01. Our values is fainter but is based on seven independentfairly consistent measurements. From the compilation by Pottasch[S] we find a visual magnitude V_m=14.4 for NGC 2867 while we derived from our own data a value 0.6 fainter. The resulting value for NGC 5189 presented here is almost one magnitude fainter than that reported by Reay et *al.*[9]. From the analysis of Fabry-Perot images at several wavelengths those authors achieve a good discrimination between the nebula and the star, deriving a visual magnitude V=14.0. Following Reay and Pottasch[10] (private comunication) there were reports of even fainter magnitudes for NGC 5189, rising the possibility of a real time variability.

As a consequence of the fainter magnitudes that we have derived for NGC 2867 and NGC 5189, we found that the Zanstra temperatures for the central stars of these planetaries are somewhat higher than those obtained respectively by Pottasch[5] and Gathier[11]. The discrepancy between our results and those by Reay *et al.*[9] for NGC 5189 reflects mainly the difference in the adopted $H\beta$-flux. Our measured value is almost a factor of two higher. Figure 1 shows the $H\beta$-flux for NGC 5189 as a function of the diaphragm dimension. This illustrates the importance of measuring extended nebulae with the largest diaphragms possible, otherwise radiation could be lost. Taking into account gives in this case only a lower limit to the effective temperature of the star, with the $T_z(HeII)$ temperature certainly much nearer to reality. In fact, the color temperature derived by Pottasch[5]; $T_c = 100000$ K, agrees much better with the value obtained herein from the $HeII$ λ4686 line.

4. THE INTERSTELLAR REDDENING

Since the radio emission from the nebulae is practically not affected by the interstellar grains, the observed flux in this spectral region can be used to predict the $H\beta$ flux. The radio emission is due to thermal Bremsstrahlung and in this case the emission rate per unit volume and per frequency interval is

$$q_\nu = 6.72 \times 10^{-38}\ \xi(Z)\ g_{ff}\ \frac{e^{-\frac{h\nu}{kT_e}}}{T_e^{1/2}}\ n_e\ n_p \qquad (6)$$

where $\xi(Z)$ is a function of the charge and densities for ions other than hydrogen, g_{ff} is the Gaunt factor and the other symbols have their usual meaning.

The $H\beta$ emission rate per unit volume is

$$q_{H\beta} = \alpha_{H\beta}(T_e)\ h\nu_\beta\ n_e\ n_p \qquad (7)$$

If the nebula is optically thin to the radio emission, the predicted $H\beta$ flux is

$$F^0_{H\beta} = \frac{q_{H\beta}}{q_\nu}\ S_\nu \qquad (8)$$

where S_ν is the observed radio-flux. The color excess $E(B-V)$ is given by

$$E(B-V) = 0.682\ \log \frac{F^0_{H\beta}}{F_{H\beta}} \qquad (9)$$

relating the ratio between the predicted and the observed $H\beta$ flux.

Table 5 shows the resulting color excess for planetaries in the galactic bulge. The radio fluxes and the angular radius given respectively in columns two and three are from Gathier et *al.*[12]. Table 5 also gives the electron density for those nebulae estimated from the equation

$$n_e = 8.86 \times 10^9 \left[\frac{F^0_{H\beta}}{D_{kpc}}\right]^{1/2} \frac{t^{0.439}}{\Theta^{3/2}} \qquad (10)$$

where $F^0_{H\beta}$ is the de-reddened $H\beta$ flux, D is the distance to the nebula in kiloparsecs, t is the electron temperature in units of 10^4 K and Θ is the angular radius in arc-seconds. In our calculations we have assumed D = 8 kpc and $T_e = 10^4$ °K for all these objects suspected to be in the bulge of our galaxy.

Table 5

OBJECT	$S_\nu\,(mJy)$	Θ''	$E(B-V)$	n_e (cm^{-3})
PK2-3.3	15	0.75	0.50	1.0×10^4
PK2-3.5	24	1.00	0.57	8.4×10^3
PK2-4.1	31	0.32	0.62	5.3×10^4
PK6-3.3	51	1.05	0.89	1.3×10^4
PK6+8.1	47	0.55	0.80	2.9×10^4

Table 6 compares for the remaining planetaries the color excess derived from different methods. In the third column are shown the present results using the radio and the $H\beta$ fluxes. The fourth and the fifth columns give the color excess derived from the comparison between the observed and the calculated line ratios for hydrogen (Balmer lines) and $HeII$. The last column gives the color excess derived from the λ2200Å interstellar feature. These results are from Gathier[11]. Excepting NGC 2452, the different methods agree fairly well and our new value for the $H\beta$ flux for NGC 5189 eliminates the discrepancy existing before.

5. CONCLUSIONS

We present new measurements of $H\beta$ fluxes from 13 planetary nebulae, including five objects in the galactic center with no fluxes hitherto measured. The actual data for these objects, combined with VLA measurements at 5GHz allowed an evaluation for the color excess and

Table 6

OBJECTS	S_ν (mJy)	E B–V			
		PRESENT	BALMER DEC.	*HeII* LINES	UV
N2440	422	0.35	0.30	0.32	-
N2452	55	0.51	0.37	-	-
N2792	122	0.65	0.53	0.65	-
N2867	252	0.30	0.28	0.20	-
N5189	413	0.43	0.33	-	0.40

the nebular electron density for these planetaries. The relatively high electron densities derived for those nebulae indicate a selectioneffect in the sense that only high surface brightness objects have been detected in the galactic center.

We emphasize the importance of using large aperture diaphragms when measuring nebulae of low surface brightness. NGC5189 is a good example, since for this objects we obtain an $H\beta$ flux almost twice the figure currently found in the literature. On the other hand, the different magnitude estimates for the central star of that nebula brings about the question regarding the existence of time variabilities. New observations of this central star are badly needed.

We are very grateful to Dr. Jarbas Castro Neto from the Instituto de Física e Química de São Carlos for his excellent work in preparing the interferential filters for us. The choice of most of our programme objects were motivated by a constant contact with Dr. S.R. Pottasch.

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Resumo

Apresentamos para 13 nebulosas planetárias novos fluxos $H\beta$ medidos no Observatório Astrofísico Brasileiro. São incluídos na nossa amostra 5 objetos do bojo galáctico com fluxos desconhecidos até o momento. Essas medidas, combinadas com o fluxo rádio observado em 5GHz, são utilizadas para a determinação do excesso de cor dos objetos observados. São também determinadas para alguns desses objetos as magnitudes a A4819 Å e temperaturas de Zanstra da estrela central.