ULTRAVIOLET PHOTOMETRY OF PLANETARY NEBULAE

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ABSTRACT

Nine of the planetary nebulae observed by the Wisconsin filter photometers are compared with 15 Monocerotis in the spectral region 1430-4250 Å. The data are corrected for the degradation of the filters of stellar photometer number four with time. Comparisons with simple models indicate that most of the observed nebulae are subject to some interstellar extinction in the far ultraviolet. However, NGC 246 and NGC 1360 appear to be nearly unreddened. Thus far no unexpected features have been found in the observations.

This is a preliminary discussion of ultraviolet photometry of nine planetary nebulae by the filter photometers of the Wisconsin Experiment Package on OAO-2. The observed nebulae were selected on the basis of total brightness and estimated small interstellar absorption. At the present only a small amount of the data has been reduced and compared with a simple model of the nebulae. When the study is complete, I expect to be able to check theories of nebular emission, to find reddening constants for the observed nebulae, and to find lower limits for temperatures of some of the central stars.

There may be some question about the accuracy with which objects as faint as planetary nebulae can be observed with the OAO. One observational problem is that, in many cases, the dark noise is larger than the signal collected by the eight-inch telescopes. Fortunately, if the OAO is not near the South Atlantic Anomaly, the dark noise usually varies smoothly with time (McNall 1971). Therefore, this contribution can be accurately subtracted from the observations if the dark noise has been measured at the beginning and end of an observational sequence and at some intermediate point. A second problem is the possibility that the 10' field of view of the telescopes will include other faint stars that would confuse the measurements. This is a possible hazard for the measurement of both the star and the sky background. However, the nebulae and their central stars emit more strongly in the far ultraviolet than the average background star. Thus, contamination usually would be limited to the longest wavelength observations. In practice, I have found that even long wavelength measurements can be quite accurate. Observations have been made of peculiar O and B stars as faint as the 12th magnitude. The ratios, in magnitudes, of the measurements of these faint stars to the measurements of brighter stars at 4250 and 3320 Å agree with the differences in ground-based B and U magnitudes. Moreover, at shorter wavelengths the differences in magnitudes between the faint stars and brighter stars with the same B-V and U-B colors agree with the differences in visual magnitudes to $0^{m}_{.}3$ and usually better. This is good agreement since the spectral types of the faint stars are not well defined and the stars may have abnormal ultraviolet fluxes. Hence, I am convinced that blue objects as faint as the 12th magnitude can be observed meaningfully by the OAO.

Unfortunately, the shortest wavelength filters on OAO, those of stellar photometer 4 (Code _et al_. 1970), have degraded since launch. Since very short wavelength observations are necessary for the study of planetary nebulae, I have investigated the behavior of these filters as a function of time. In Figure 1 the relative loss of filter sensitivity, in magnitudes, for early type stars is plotted against the number of orbits since launch. This degradation was determined by comparing observations of eleven O and B stars which have been observed repeatedly during the lifetime of the satellite. Filter 1, the 1550 Å filter, has undergone the least amount of change. Filter 3, the 1430 Å filter, has degraded rapidly after orbit 9000. Filter 4, the Lyman alpha filter, has degraded continuously since launch and has suffered the greatest loss of sensitivity. The rate of degradation of filter 3 and of filter 4 has lessened greatly since orbit 13000. The mean deviation of the observations from these curves is $0^{m}_{.}04$ for filter 1, $0^{m}_{.}05$ for filter 3, and $0^{m}_{.}07$ for filter 4. A change in the effective wavelength of these filters has apparently accompanied the loss of sensitivity. The filters have become relatively more opaque to light of shorter wavelengths. Therefore, those stars which emit most of their light at longer wavelengths appear brighter in recent observations than predicted from the curves in Figure 1.

The results of the observations of the nebulae are presented in Table 1. In order to avoid questions of calibration and

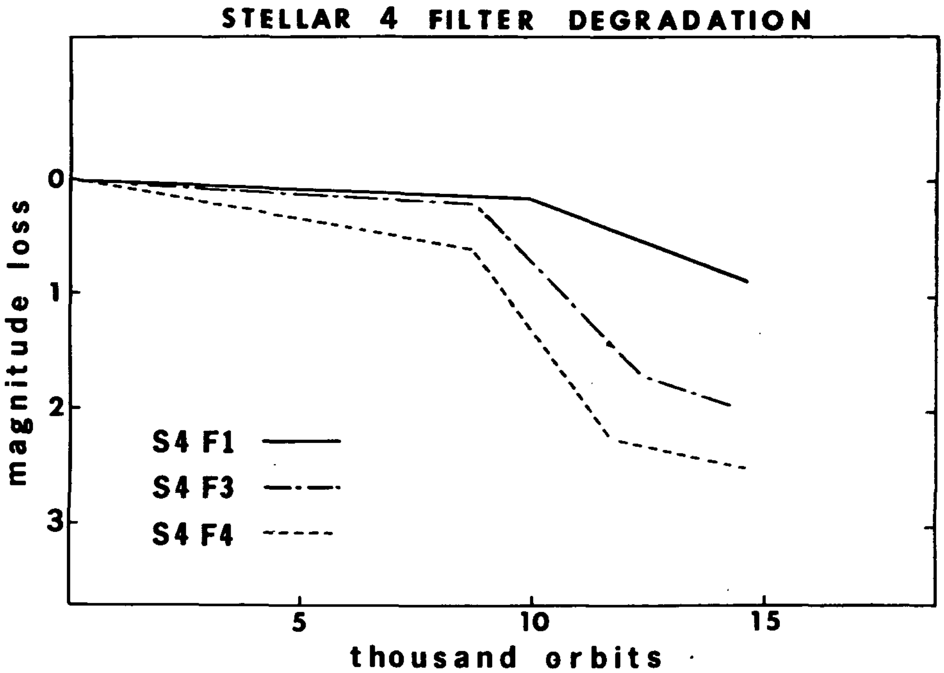

Figure 1.—The loss of sensitivity of the filters of stellar photometer four as a function of time between launch and orbit 15,000. Each orbit is approximately 100 minutes. These curves were derived for O and B stars.

to highlight features of the observations, the results are presented in the form of magnitudes relative to 15 Monocerotis (O7, V = 4.65, B-V = -0.25). These measurements have been corrected to the launch date for the degradation of the stellar 4 filters and for the decay of the ^{90}Sr calibration sources. I have not used the data from the Lyman alpha filter because for that filter the sky background is too bright in comparison to the nebulae. I have not used data from stellar 3 filter 5 because, in recent orbits, the amount of light transmitted by that filter is a function of the position of the star image on the filter. I have not used the data from stellar 2 because red leaks in its filters make sky brightness measurements for planetary nebulae unreliable.

Instead of discussing the details of all of the observations, I will speak mostly about two representative objects, NGC 246 and NGC 6826.

NGC 246 in the far ultraviolet appears to be an unreddened planetary with a moderately bright nebula and central star. It is similar to NGC 1360, but is fainter than that nebula.

Table 1. The ratios, in magnitudes, of the ultraviolet fluxes of the nebulae to those of 15 Mon. The estimated errors in the table refer only to the measurements of the nebulae. No corrections have been made for interstellar extinction.

Nebula	S1F3 4250 Å	S1F1 3320 Å	S1F4 2980 Å	S3F2 2460 Å	S3F1 1910 Å	S4F1 1550 Å	S4F3 1430 Å	*
NGC 40	5.95±0.14	6.88±0.17	7.49±0.26	8.53±0.22	8.53±0.21	8.40±0.50	8.45±0.63	
NGC 246	6.10±0.08	6.19±0.05	6.37±0.05	6.32±0.02	6.27±0.02	5.94±0.04	5.95±0.12	1,2
IC 418	4.93±0.03	5.05±0.03	5.37±0.03	5.77±0.01	6.10±0.02	6.03±0.04	---	1,2
NGC 1360	5.72±0.12	5.96±0.09	5.89±0.08	5.81±0.02	5.70±0.03	5.31±0.06	5.37±0.11	3
NGC 1535	6.29±0.20	6.44±0.15	6.74±0.17	6.94±0.03	7.06±0.07	6.70±0.18	6.66±0.52	
NGC 3587	6.74±0.26	7.53±0.38	8.20±0.62	8.37±0.07	8.54±0.22	8.20±0.60	7.96±2.0	
NGC 6543	4.78±0.05	5.21±0.04	5.64±0.05	---	---	5.93±0.06	6.04±0.06	2
NGC 6826	5.27±0.05	5.45±0.04	5.57±0.03	5.75±0.01	5.81±0.02	5.67±0.07	5.84±0.09	1,2
NGC 7293	5.22±0.07	5.77±0.06	6.34±0.07	6.68±0.05	6.73±0.04	6.60±0.09	6.82±0.12	

*1. Nebula observed twice.
2. Two separate measurements made for sky background.
3. Sky background is the mean of three nearby sky measurements.

Figure 2 shows the photometry of NGC 246 relative to 15 Mon. The data for NGC 246 are the means of two observations and the sky background data are the means of observations of two skys. The observations are compared with a simple model which is derived from the results of ground-based observations. This model uses only the hydrogen two-photon and recombination continuum radiation (Spitzer and Greenstein 1942, Seaton 1960, and Brown and Mathews 1970), the observed relative line fluxes (Minkowski 1942), and the He II 1640 Å flux estimated from the He II 4686 Å line strength. The central star was represented by the model atmosphere #204 (T_{eff} = 200,000°K and log g = 7.0) of Hummer and Mihalas (1970). This atmosphere was adjusted to the B magnitude of Liller and Shao (1968). The Hβ flux was estimated from the 2695 MHz radio measurement of Davies et al. (1967). The relation between the nebular flux and the stellar magnitude was derived using the absolute flux measurement of Vega by Oke and Schild (1970). The nebular temperature was assumed to be 10,000°K. Every hydrogen recombination which entered the n = 2 level for the first time in the 2^2S state

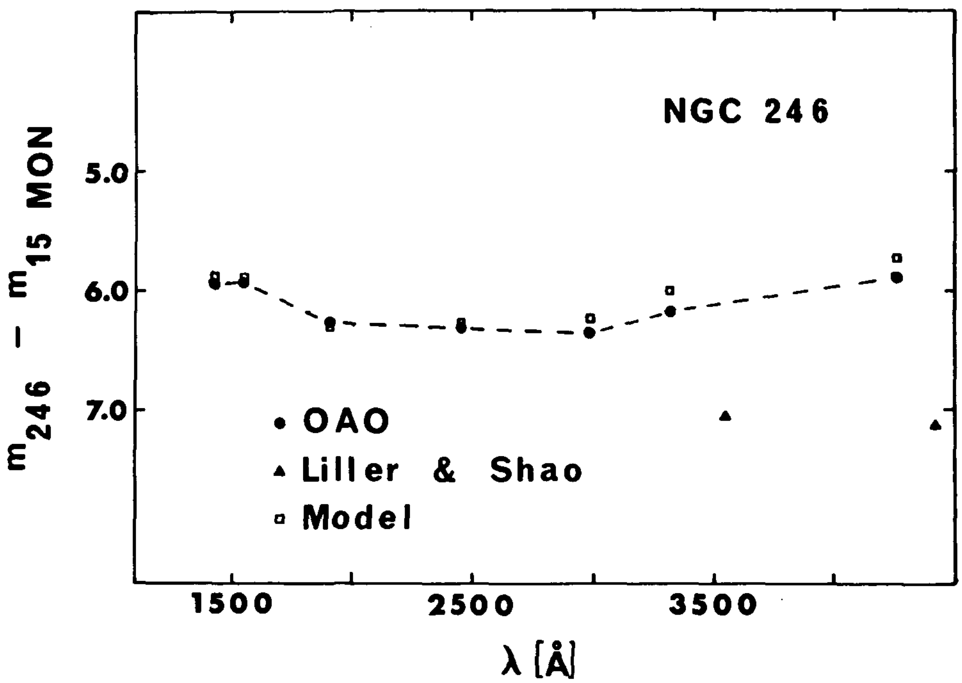

Figure 2.—Filter photometry of NGC 246 relative to 15 Mon. The observations of Liller and Shao (1968) are B and U magnitudes of the central star. The model nebula is described in the text. No corrections have been made for ultraviolet extinction. Note that the observed and model nebulae nearly coincide at wavelengths shorter than 2500 Å.

was assumed to result in two-photon emission. The calculated model was related to the OAO observations by the normalization factors derived by Code (1970) from B3 V models and observations. No reddening corrections were applied. Although a number of approximations were made in constructing the model, the fit with observations is good. In the model most of the radiation at wavelengths longer than 2500 Å is contributed by the nebula. At 1910 Å the model star contributes two-thirds of the flux. The He II 1640 Å emission line causes a small bump at 1550 Å. The agreement between the observations and the unreddened model indicates that this nebula is little reddened. This agrees with Kaler's (1970) estimated reddening constant of 0.0.

NGC 6826 is typical of most other nebulae observed in that the interstellar absorption appears to be significant. Figure 3 shows the photometry of NGC 6826 relative to 15 Mon. The model nebula was generated in the same manner as that of NGC 246. The relative line fluxes are from O'Dell (1963) and the H_β flux is from Collins, Daub and O'Dell (1961). The magni-

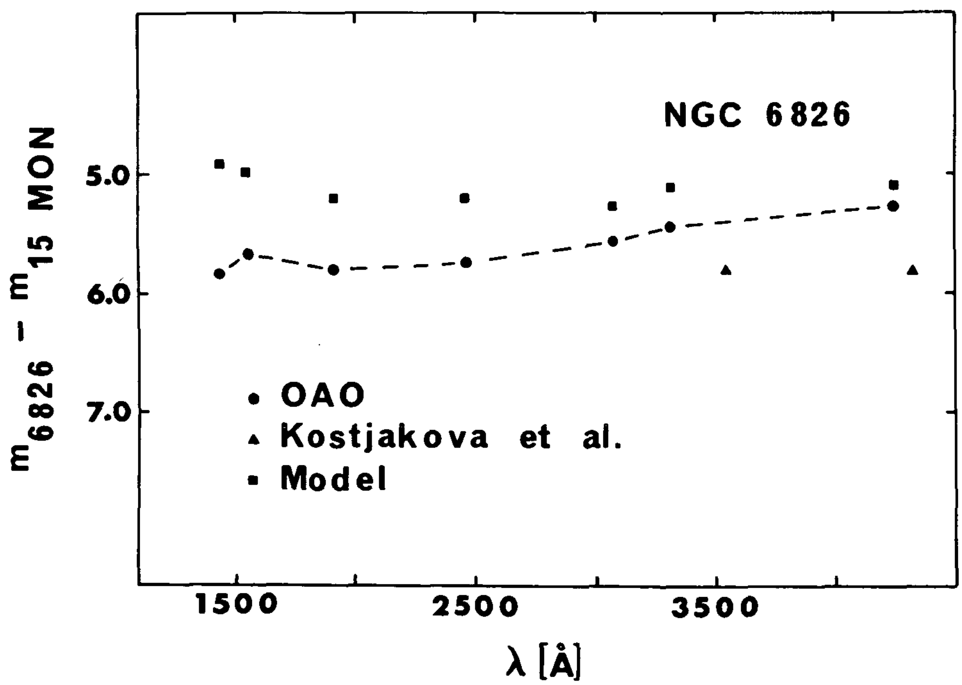

Figure 3.—Filter photometry of NGC 6826 relative to 15 Mon. The observations of Kostjakova et al. (1968) are B and U magnitudes of the central star. Note that the model deviates increasingly from the observed nebula towards short wavelengths. This trend can be removed with the "average" extinction curve of Bless and Savage (1972) if a reddening constant of 0.19 is assumed.

tude of the central star is from Kostjakova et al. (1968). As is seen in the figure, the model nebula increasingly deviates from the observed nebula at short wavelengths. This trend could be eliminated with the average reddening curve of Bless and Savage (1972) if the E(B-V) were 0.14. This color excess corresponds to a reddening constant of 0.19. This reddening constant is consistent with the values of 0.24 given by Osterbrock (1964) and of 0.18 given by Kaler (1970), but it disagrees with the values near 0.0 given by Thompson, Colvin and Stanley (1967) and by Terzian (1968).

NGC 7293 causes special problems because its angular extent is larger than the field of view of the photometers. The observations presented here were centered about 3.'5 north and 1.'5 east of the center of the nebula. There is a possibility that the four telescopes were not perfectly aligned so that the data from different telescopes may refer to different parts of NGC 7293.

In conclusion, the OAO observations of planetary nebulae appear to be good. Thus far no unexpected features have been found. New observations of planetaries and reductions of earlier observations are still being made. With more refined models, I expect to extract more information from the data.

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