THE ASTROPHYSICAL JOURNAL, 202:415–420, 1975 December 1

THE ROCKET-ULTRAVIOLET SPECTRUM OF THE PLANETARY NEBULA NGC 7027

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Received 1975 May 5

ABSTRACT

An ultraviolet spectrum of NGC 7027 was obtained with a rocket-borne telescope. The observed fluxes are given on an absolute basis, and upper limits are given for the strongest predicted lines which were not observed. The extinction correction was made on the basis of the observed and calculated line ratios for the hydrogenic recombination line of He II at 1640 Å to Hβ. The extinction is in agreement with ground-based determinations. When corrected for extinction, the C IV resonance line at 1549 Å is in good agreement with the intensity calculated from models, but the C III] intercombination line at 1909 Å is a factor of 10 too bright. The addition of dielectronic recombination to the models sufficiently changes the C III concentration to reduce the discrepancy to a factor of 4. The abundance of carbon is assumed to be 2×10^{-4} that of hydrogen. Using carbon abundances for the Sun, which are up to 3 times higher, this discrepancy disappears, and there must be attenuation in the C IV line. Since the optical depth is $\sim 10^4$ at the line center, no appreciable number of absorbing grains can exist in the C IV-producing region of the nebula.

Subject headings: abundances, nebular — interstellar extinction — planetary nebulae — spectra, ultraviolet

I. INTRODUCTION

The spectra of planetary nebulae have not yet been observed from orbiting spacecraft. Either the spectra are too faint or the pointing requirements are too stringent, or both. Photometry of planetary nebulae was done with the wide bandpasses of the OAO-2 photometers (Holm 1972) and by the Astronomical Netherlands Satellite (Van Duinen 1974). The expected emission spectrum in the ultraviolet was discussed by Osterbrock (1963); and Flower (1968) constructed detailed models of high-excitation nebulae which give quantitative estimates for the intensities of the strongest ultraviolet lines. Other models capable of predicting ultraviolet line spectra include those of Harrington (1968), Kirkpatrick (1970), and Sage (1974). The fundamental physical processes governing the ionization and thermal structure in nebulae seem to be well understood (Osterbrock 1974). However, some uncertainty in the interpretation of observations stems from the limited range of ionic species represented in the visible region of the spectrum. Therefore, observations of a planetary nebula in the ultraviolet would be valuable. The continuum flux could also be measured to see that all of the physical processes that lead to continuous emission have been included. In addition, many of the ultraviolet emission lines are more sensitive to the physical conditions present in the nebula than are the visual lines.

The continual improvements in rocket-pointing controls coupled with the development of sensitive ultraviolet image tubes make feasible the observation of the ultraviolet spectrum of a planetary nebula. The choice of the planetary nebula to be observed is still limited by a number of constraints. The absolute pointing is not accurate enough to image a planetary nebula on a slit, so a slitless spectrograph must be used. To get the entire spectrum on a 40-mm image tube, rather low dispersion is necessary in the spectrograph. The angular size of the planetary nebula must be small to prevent overlapping images due to the low dispersion and drift in the pointing system. The central star must be faint so that the stellar spectrum does not obscure the nebular spectrum. A high surface brightness for the planetary nebula is essential in order to observe it in the short period of time that the rocket is above the atmosphere. A planetary nebula with a high-excitation spectrum should have the most strong ultraviolet lines. Furthermore, the planetary nebula must be within a few degrees of a first or second magnitude star in order to update the gyroscopes of the control system. NGC 7027 is the best observed of all planetary nebulae and fits all the special requirements for rocket observations. The one serious problem with the choice of NGC 7027 is that, with a color excess $E(B - V) \sim 1$, a severe attenuation of the ultraviolet lines will occur due to interstellar extinction. In § II the observational equipment and procedures are described, in § III we present our results, and in § IV the results are compared with theoretical models for a high-excitation nebula.

II. OBSERVATIONS

The 33-cm telescope with spectrograph described by Stecher (1970) was flown on Aerobee 26.026 at 07^h30^m UT on 1974 June 22 from the White Sands National Range. A concave grating with 600 lines mm^{-1} and a folding mirror in the spectrograph section imaged a $17' \times 24'$ area of the sky onto the 40-mm cesium telluride cathode of a Micro-Channel Plate (MCP) image converter manufactured by Galileo Electro-Optics Corp. The phosphor output screen of the MCP was coupled to 35-mm Kodak IIa-O film by fiber optics. A rate integrating gyro system (RIGS) updated on two guide stars by a STRAP IV star-tracker was used to position the target in the small entrance aperture. To minimize pointing errors, the first and second guide stars were separated by about 45° and the second guide star was close to the target. For NGC 7027 the nearer guide star, α Cyg, was 6° distant.

The window of the MCP is magnesium fluoride and the four optical surfaces are coated with aluminum overlaid with magnesium fluoride. The thickness of the coating on the telescope secondary and spectrograph folding mirror is adjusted to minimize the sensitivity to Lα airglow to prevent fogging of the film over the entire field of view. High sensitivity across the MCP is maintained from 1300 to 2900 Å with a linear dispersion of 45.82 Å mm^{-1}. Laboratory exposures demonstrate that the scale is linear to ± 1 Å for the entire wavelength range. However, the actual wavelengths change by 58 Å $arcmin^{-1}$, depending on the position of the source in the field of view.

In order to establish wavelengths on the flight film, three of the strongest expected lines are identified with three of the clearest features observed. During the 90 s exposure on NGC 7027, the RIGS drift was 20″ perpendicular to the dispersion and 35″ in the dispersion direction, making the emission lines 35 Å wide. The positions of the line centers can be measured to ± 3 Å. Within this uncertainty, the separation of the three lines agrees with their identification as C IV 1549 Å, He II 1640 Å, and C III] 1909 Å. This identification implies an absolute pointing error in the dispersion direction of 2′, comparable to the error of 3′ perpendicular to the dispersion. If the pointing error in the dispersion direction was as large as 6′, the wavelengths of the three features could be as much as 230 Å more or 470 Å less. No other identifications appear likely within the constraints of the pointing errors and separation of observed features.

III. RESULTS

An absolute calibration of the complete payload was done before launch. The basic absolute reference is a photodiode certified by NBS. The instrumental response is measured in terms of film density. The calibration was accomplished on the facilities described by Stecher (1970) using the same basic vacuum techniques detailed by Bohlin *et al.* (1974). The primary mirror in the payload was illuminated by a collimated, monochromatic beam of light in a large vacuum chamber. A standard photomultiplier tube monitored the beam flux while a pre-monochromator scanned the spectrum of hydrogen in a Hinteregger lamp. The photomultiplier served as a secondary standard with a sensitivity determined by comparison with the NBS diode.

The absolute calibration has three independent parts: (1) a film density versus relative exposure level, found by scanning the pre-monochromator at different, precisely known rates; (2) an absolute sensitivity versus wavelength at the center of the field of view for unit relative exposure corresponding to a density of 0.4 on the film; and (3) a relative sensitivity over the field of view to account for vignetting in the baffling system. No failure of the reciprocity law should occur, because all light incident on the film has been amplified by the MCP. The low input flux levels and rapid scanning speeds necessary to calibrate the sensitive payload were difficult to monitor on a mechanical chart recorder. The scatter in these calibration data led to an estimated error of a factor of 1.5 in the measured fluxes, barring any systematic effects caused by the somewhat uncontrolled thermal environment of the flight film.

The upper curve in Figure 1 is a scan of the spectrum of NGC 7027 with the microdensitometer slit equal to the 20″ by 35 Å size of the monochromatic images. The lower curve is a scan with the same microdensitometer slit offset below the planetary spectrum by two slit heights. The background noise is considerably above the level observed in a 90 s exposure in the laboratory. The cause for most of the excess noise observed in flight is probably ions that have been attracted by the 6000 volt negative potential on the MCP cathode, creating photons which produce photoelectrons. Applying a retarding potential of +28 volts to the primary mirror for the succeeding flight of the payload on Aerobee 26.027 seems to have solved the ion problem. The increase in the noise level at longer wavelengths reflects an increase in cathode sensitivity on that part of the MCP.

Because of the noise, only the four emission lines in Figure 1 at the shorter wavelengths have a high probability of being real. Table 1 summarizes the measurements of the observed spectrum, listing wavelengths, line identifications, and flux values in the first three columns. Column (4) compares the observations with the measured Hβ flux; the extinction, as derived in § IV, appears in column (5), and is applied to produce the corrected intensity ratio at the nebula in column (6). The observations of the identi-

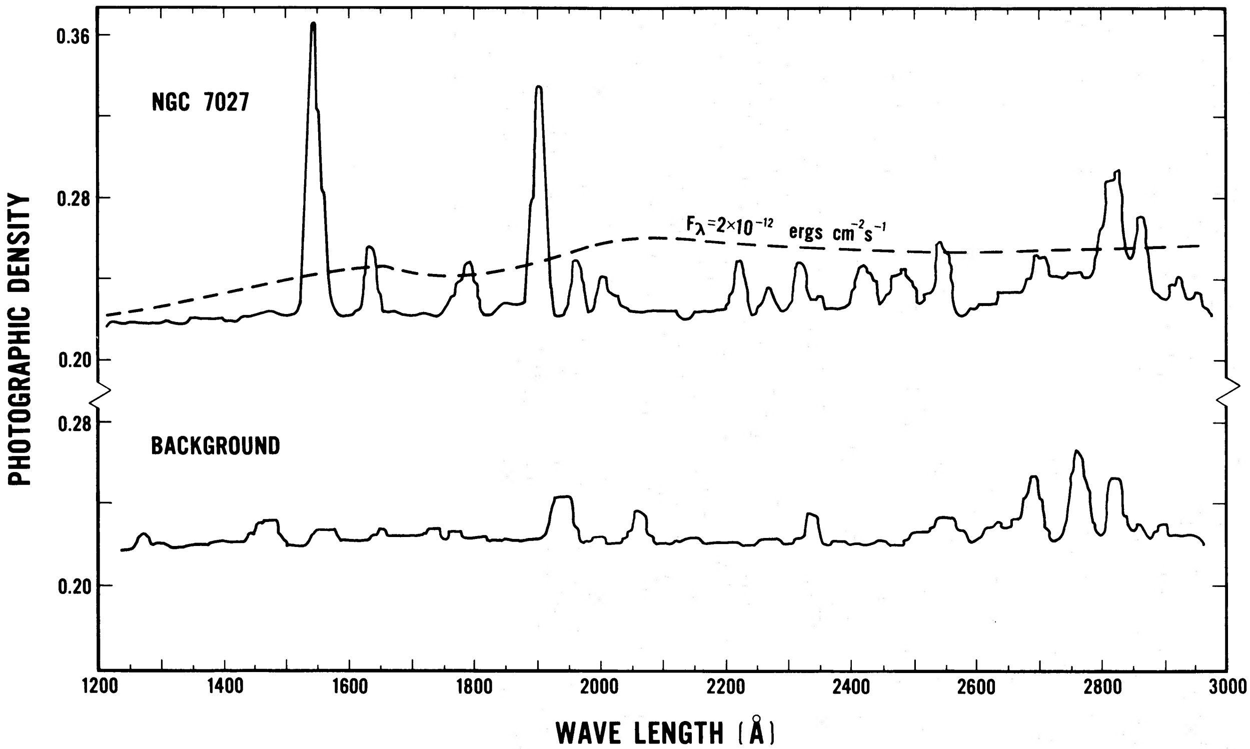

FIG. 1.—Ultraviolet spectrum of the planetary nebula NGC 7027 (*upper solid line*). The lower solid line is a scan of the flight film two slit heights below the nebular spectrum, and represents the typical noise level of the data. The dashed line is proportional to the instrumental sensitivity and defines the flux corresponding to 2×10^{-12} ergs cm^{-2} s^{-1} with a constant photographic fog density of 0.22 as the zero level.

fied lines and upper limits to predicted lines are compared with models in the last column. While none of unidentified lines at longer wavelengths greatly exceeds the typical noise level, the total signal exceeds the background, indicating that some of the features are probably from NGC 7027.

IV. DISCUSSION

NGC 7027 is very heavily obscured by interstellar material. Miller and Mathews (1972) find the color excess to be $E(B - V) = 0.91$ from the Balmer lines, and that $E(B - V) = 1.01$ gives the best fit to their continuum measures. In order to compare the observed fluxes with models, we must correct the fluxes for interstellar extinction. The precise form of the extinction curve in the ultraviolet cannot be predicted for a specific line of sight (Stecher 1965, 1969; Bless and Savage 1972.) Therefore, to correct the data for extinction, the average curve is normalized by taking a model for NGC 7027 which satisfactorily predicts the line intensities in the visible, and using it for the line ratio between Hβ and an emission line in the ultraviolet. The absolute intensity of Hβ (6.25×10^{-11} ergs cm^{-2} s^{-1} from Miller and Mathews 1972) and the absolute calibration of the flight spectrum determine the extinction, if the theoretical line ratio is known. The most reliable line ratio is from the He II line at 1640 Å and Hβ, since they are both recombination lines of one-electron systems. From the predictions of a model, which will be discussed later, an extinction correction of 4.77 magnitudes between λ4861 and λ1640 is obtained. This extinction, when used to normalize the average extinction curve of Cashdollar and Code as adopted by Code *et al.* (1975), gives a color excess of $E(B - V) = 1.09$. The rather small increase between this result and that of Miller and Mathews could be due to variations across the nebula which are known to be important (Balick *et al.* 1973) or due to using the average extinction curve. The uncertainties in the absolute calibrations and the statistics of the observational quantities could also account for the difference.

Sage (1974) has computed models for NGC 7027 that contain condensations and obtains a very good fit to the visual observations of this nebula. Unfortunately, neither his models nor any other *single* model of a high-excitation planetary in the literature includes a prediction of the theoretical intensities of He II λ1640, C IV λ1549, and C III] λ1909. We have, therefore, constructed a number of model nebulae that are spherical and homogeneous. The references to the relevant atomic parameters necessary for the solution of the equations of ionization and thermal equilibrium for ions of the atoms H, He, C, N, O, and Ne are cited in a paper by Buerger (1973), with the exception that the nonhydrogenic radiative recombination rates of Tarter (1971, 1972, 1973) were

TABLE 1

OBSERVED FLUXES FROM NGC 7027

λ (1)	Ion (2)	Flux (10^{-11} ergs cm^{-2} s^{-1}) (3)	$F(\lambda)/F(H\beta)$* (4)	Extinction $A_\lambda - A_\beta$ (mag) (5)	$I(\lambda)/I(H\beta)$ (6)	$I(\lambda)$ Obs./$I(\lambda)$ Model (7)
			Line Features			
1549.........	C IV	1.06	0.17	5.00	17.0	1.14
1640.........	He II	0.28	0.045	4.77	3.6	1.00
1793.........	...	0.23	0.037	4.70	2.8	...
1909.........	C III]	0.62	0.098	5.29	12.8	10.2
1964.........	...	0.18	0.029	5.60	5.0	...
2008.........	...	0.10	0.016	6.10	4.4	...
2224.........	...	0.17	0.027	6.31	9.0	...
2321.........	...	0.16	0.026	5.36	3.6	...
2424.........	...	0.16	0.026	4.57	1.7	...
2548.........	...	0.21	0.034	3.83	1.2	...
2821.........	...	0.39	0.063	2.72	0.8	...
			Line Upper Limits			
1240.........	N V	< 0.67	< 0.11	6.68	< 52	< 17
1334.........	C II	< 0.27	< 0.04	5.84	< 8.7	...
1407.........	O IV	< 0.18	< 0.03	5.36	< 4.2	< 10
1488.........	N IV]	< 0.13	< 0.02	5.15	< 2.3	< 2.0
			Continuum Upper Limits			
		(10^{-14} ergs cm^{-2} s^{-1} Å^{-1})	(Å^{-1})		(Å^{-1})	
1500.........		< 3.8	$< 6.1 \times 10^{-4}$	5.14	< 0.069	...
1800.........		< 3.1	$< 4.9 \times 10^{-4}$	4.70	< 0.037	...
2100.........		< 1.9	$< 3.0 \times 10^{-4}$	6.84	< 0.16	...
2400.........		< 3.2	$< 5.2 \times 10^{-4}$	4.73	< 0.04	...
2700.........		< 5.0	$< 8.0 \times 10^{-4}$	3.14	< 0.01	...
2800.........		< 6.7	$< 11 \times 10^{-4}$	2.83	< 0.01	...

*$F(H\beta) = 6.25 \times 10^{-11}$ ergs cm^{-2} s^{-1}.

employed in the present models. Since dielectronic recombination may be significant at gas temperatures of ~15,000 K (Flower 1969; Asselbergh and van Rensbergen 1969), the final calculations were repeated with the inclusion of the rates given by Aldrovandi and Péquignot (1973). These results will be discussed later in this paper. The analysis of the He II λ1640, C III] λ1909, and C IV λ1549 transitions required some additional or updated atomic parameters. The effective recombination coefficient $\alpha_{3\to 2}$ for He II was taken from Brocklehurst (1971). The radiative transition probabilities for C III] λ1909 are from Loulergue and Nussbaumer (1974) for the intercombination and magnetic quadrupole transitions, and from Wiese *et al.* (1966) for the fine-structure transitions among the $^3P^0$ levels. Collision strengths for the λ1909 lines are those of Flower and Launay (1973) for excitation from the ground state to the $2p\,^3P^0$ levels, and Blaha (1968) for transitions between the fine-structure levels. The relevant data for C IV were taken from Leibowitz (1972) and Bely (1966) for radiative and collisional processes, respectively.

We have combined the observational results of Miller and Mathews (1972) for the lines of [O III] $\lambda\lambda$4363, 4959, 5007 and He II λ4686 and their distance of 1.77 kpc, with the C, N, O, and Ne abundances of Sage (1974) in an effort to produce a model representative of the high-excitation region of NGC 7027. A suitable fit was achieved for the rather high stellar temperature of 1.7×10^5 K which was used in Sage's Model 2. Specifically, our models give intensities relative to Hβ = 100 of I(He II λ4686) = 48.1, I(O III λ4363) = 27.2, I(O III λ4959) = 531.6, and I(O III λ5007) = 1557 for a stellar radius of 0.11 $R_\odot$ and a ratio of inner to outer nebular radius of 0.10. The outer nebular radius was 0.049 pc and the hydrogen density was 1.25×10^4 atoms cm^{-3}. The flux distribution for the central star was extrapolated from the 200 series models of Hummer and Mihalas (1970). In Table 1, column (6) gives the intensity ratio between the observed lines and Hβ after correcting for extinction. Column (7) contains the ratio of the observed and unreddened intensity to that of the models. The $\lambda\lambda$1549, 1640, and 1909 lines are from our model, and the others are from Sage's model 2. The He II line at λ1640 agrees with the model by definition, since the extinction correction was determined from it. If Miller and Mathews's continuum value for the color excess is used with the Cashdollar and Code average extinction curve, the He II line would still be within 50 percent of the model. The λ1909 intercombination line of C III is a factor of 10.2 times brighter than calculated in our model. Sage's model gives the same result. The λ1488 intercombination line of *N* IV, which is the similar line from the two-electron outer shell system next along the isoelectronic sequence, was not observed; but the observations are good enough to demonstrate that the model does not seriously underestimate the strength of λ1488. The models predict nearly the same intensities for both of these lines, so while the λ1488 N IV] line intensity is consistent with our failure to observe it, the λ1909 C III] line intensity is brighter than the models'.

These two lines, λ1909 and λ1488, are excited mainly by electron collisions, with recombination contributing only two percent of the intensities of the C III line. In the solar chromosphere the λ1909 line is known to be a factor of 3 too bright in comparison with models for the Sun (Gabriel and Jordan 1972). This prompted a theoretical effort to verify the electron collision cross section (Flower and Launay 1973; Hershkowitz and Seaton 1973). Loulergue and Nussbaumer (1974) have indicated that the problem lies somewhere other than in the electron collision cross section. The model was changed to include dielectronic recombination using the coefficients given by Aldrovandi and Péquignot (1973), with the following interesting result. Most of the ions in the model are not affected very much by the process of dielectronic recombination, because the temperatures at which the rates are the highest are considerably above the highest temperatures found in the model. For C III this is not the case. In the innermost part of the nebula where C III is a minor constituent, the density of C III ions is increased by a factor of 20 due to the process of dielectronic recombination. The effect on the integrated line intensity of λ1909 is to increase it by a factor of 2.35, which reduces the observational discrepancy to a factor of 4. In contrast, the N IV] λ1488 intensity was increased by only 8 percent.

In the above discussion, the models have a carbon abundance of 2×10^{-4} that of hydrogen. Since this canonical value of the carbon abundance in planetary nebulae is poorly justified, its effects on the results should be considered. The observed intensity of the C IV λ1549 line agrees well with calculations, while the λ1909 C III] line is a factor of 4 more intense than predicted. The choice of the carbon abundance is in agreement with Sage, but is a factor of 3 less than the solar value (Withbroe 1971). There are several physical processes that could reduce the observed intensity of the C IV doublet without changing the C III] line. The C IV lines could be absorbed in the interstellar gas if any appreciable portion of the carbon is in the form of C IV. However, the radial velocity of the gas probably is sufficiently different from that of the planetary to minimize the effect. Another possible absorber is dust in the nebula itself. Krishna Swamy and O'Dell (1968) showed that the large infrared excess found in NGC 7027 by Gillett *et al.* (1967) could be explained in terms of thermal radiation from dust grains embedded in the nebula. The λ1909 line is an intercombination line which is optically thin. The optical depth in the center of the line for the C IV doublet is greater than 10^3, so that each photon is scattered many times before leaving the nebula. In fact, the C IV resonance lines in this nebula have an intensity and optical depth in the line center comparable to Lα. Theoretical studies of the Lα transfer problem in the nebula can be applied equally well to C IV. Panagia and Ranieri (1973) have done a Monte Carlo study of Lα transfer in a dust-filled nebula. Their case (*b*) shows that for C IV to be attenuated by a factor of 3, the optical depth due to grains need be only 0.2. Thus, if the models were to be changed to bring up the intensity of the λ1909 C III] line to meet the observations, then the λ1549 C IV line could be explained with only 0.2 mag of dust extinction in the C IV-producing region. On the other hand, the gas to color excess ratio of 5.4×10^{21} atoms cm^{-2} mag^{-1} found by Bohlin (1975), and the total column density of hydrogen in the model of $N_H = 1.9 \times 10^{21}$ atoms cm^{-2} would give 2.9 mag of extinction, assuming that the planetary has a gas-to-dust ratio the same as the interstellar medium. This would give an optical depth in the dust 13 times greater, which would greatly reduce the amount of C IV emission coming from the nebula. We therefore conclude that the number of absorbing grains in the C IV-producing region must be very much smaller than the number given by the interstellar gas-to-dust ratio. If our model has the correct carbon abundance, then no grains are likely in the C IV-producing region. If grains exist in the nebula, then they must be in the outer part where their effect on the C IV doublet is indistinguishable from that of the grains in the interstellar medium. It might also be noted that any other absorbing mechanism, such as photoionization from the 2^3S metastable level in helium, would also reduce the intensity of the C IV line. For these reasons a higher carbon abundance is probably indicated. A factor of 3 more carbon was placed in the model and the predicted C III and C IV lines were increased by a factor of 1.75, but the model then failed to give the proper intensities for the O III lines. The reason for this is that the strong cooling effect produced by the C IV lines (Flower 1969) changes the thermal structure of the model. The heating caused by the ionization of the He I 2^3S level by the 1549 Å photons was not included. Further iteration of the model was not attempted, as the accuracy limit for the data and the model was reached.

We thank J. P. Harrington for the use of his planetary nebula program, and H. Nussbaumer for providing unpublished calculations. Invaluable assistance in launching Aerobee 26.026 was obtained from G. Baker, J. Glaab, and A. Stober, and from the Sounding Rocket Division of Goddard Space Flight Center. T. Collinson was responsible for the flawless performance of the STRAP IV pointing system.

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Note added in proof.—The spectrum of NGC 7662 was recently obtained with the same instrument and a much better signal-to-noise ratio. Strong features were found at 1549, 1640, and 1909 Å, confirming their identification in NGC 7027. Also strong in NGC 7662 was the Ne IV doublet at 2440 Å.

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