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Digital Object Identifier (DOI)
http://dx.doi.org/10.1086/175476

Notes/Citation Information
Published in *The Astrophysical Journal*, v. 442, no. 2, p. 714-725.

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THE ASTROPHYSICAL JOURNAL, 442:714–725, 1995 April 1

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COLLISIONAL EFFECTS IN He I: AN OBSERVATIONAL ANALYSIS

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Received 1994 July 7; accepted 1994 October 13

ABSTRACT

Accurate and reliable helium abundances can test modern theories of galactic and primordial nucleosynthesis. Unfortunately, there is now some question whether current theory can account for collisional contributions to He I. We present new observations of two planetary nebulae (PNs) in the range λ3850–λ9650, which we use to assess the importance of collisional effects in the He I spectrum. The first object, NGC 7027, is expected to show relatively strong collisional enhancement, while the second, NGC 7026, should display only small effects. We derive new collision-to-recombination correction factors, based on new collision strengths from a 29-state quantal calculation of He I extending to $n = 5$. Our results show that the correction factors based on "standard" theory are correct, but that the errors acquired in such an observational analysis are appreciable. We find no convincing observational evidence for the existence of an unknown agent depopulating the $2\,^3S$ state in PNs.

Subject headings: atomic processes — planetary nebulae: individual (NGC 7026, NGC 7027)

1. INTRODUCTION

Because helium abundances must be known to within a few percent for studies of galactic chemical evolution and primordial nucleosynthesis, the collisional enhancement of He I lines from the metastable $2\,^3S$ level has been a topic of concern for decades. Cox & Daltabuit (1971) suggested that collisional excitation of λ5876 and λ4471 could be important in gaseous nebulae. Their results were contested on theoretical grounds by Brocklehurst (1972) and on observational grounds by Peimbert & Torres-Peimbert (1971) and Barker (1978), who suggested that their collisional rate coefficients were too large by a factor of 3. More recently, Ferland (1986), using the results of an 11-state quantal calculation by Berrington et al. (1985, hereafter BBFK), showed that while these new rate coefficients were roughly a factor of 2 lower than Cox & Daltabuit's rates at low temperatures (~5000 K), they approached the Cox & Daltabuit values at high temperatures (~20,000 K). Based on observations of the well-studied planetary nebula (PN) NGC 7027, Péquignot, Baluteau, & Gruenwald (1988) determined that the BBFK rates were too large by a factor of 1.5–2.5. This result was largely confirmed by newer quantal calculations involving a 19-state ***R***-matrix computation up to $n = 4$ (Berrington & Kingston 1987, hereafter BK). Both Peimbert & Torres-Peimbert (1987a, hereafter PTP1) and Clegg (1987) derived collision-to-recombination (C/R) correction factors based on atomic theory for several lines using these results. Clegg showed for a sample of PNs that these corrections lowered the calculated He abundances by an average value of 10%.

There remains some uncertainty in these collisional rate coefficients, however. PTP1 found that for a sample of PNs, the He abundance determined from 6678 was discrepant with abundances determined from other lines. They then assumed that the C/R correction factors were multiplied by a factor γ and proceeded to determine this factor by requiring that the 6678 abundance match that obtained from other lines. Their γ values ranged from 0.25 to 0.45. In another paper, Peimbert & Torres-Peimbert (1987b, hereafter PTP2) found a discrepancy in the observed versus predicted ratios of λ10830/λ5876 and λ7065/λ5876 for several PNs. Here they define γ as the ratio of collisional plus radiative de-excitation of the $2\,^3S$ level to the total depopulation rate. They then varied the two parameters $\tau(3889)$ and γ to obtain the best fit to these two line ratios. Their average value of γ was 0.54. They attributed this discrepancy to an unknown mechanism depopulating the $2\,^3S$ level. Although several possible mechanisms have been explored, none have proven successful.

In two previous papers, Kingdon & Ferland (1991, 1993) showed that the λ10830 discrepancy for NGC 7027 can be explained by a combination of telluric absorption of this line, line destruction by dust within the nebula, and observational uncertainties in measuring the λ10830 line intensity. Sawey & Berrington (1993) have completed the next step in their He atom calculations. This involves a 29-state quantal calculation including levels up to $n = 5$. In addition, Smits (1994) has recently completed a revised computation of the He I recombination spectrum.

In light of these new results, we wish to reexamine the C/R collisional factors for other He I lines. To this end, we have obtained long-slit CCD spectra of two PNs, NGC 7027 and NGC 7026. The first of these is a hot, dense object and is predicted to have a relatively large collisional enhancement. The second object is cooler and much less dense and should therefore show only small collisional effects. Our goal is to compare observations of the relative intensities of the He I lines in these objects with theory, and thus to derive empirically the value of the depopulation factor γ. We shall also closely examine the errors encountered in each step of the reduction process to determine the uncertainties in the final results.

In § 2 we discuss our observations. Data reduction, including reddening and telluric corrections, is discussed in § 3. We present new formulae for the C/R factors in § 4 based on the new data, and calculate the value of γ from a comparison of these numbers with our observations. Finally, we discuss our results in § 5. We find no convincing evidence for an unknown process affecting the population of $2\,^3S$, but the observational uncertainties are large.

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2. OBSERVATIONS

We obtained long-slit CCD spectra of the PNs NGC 7027 and NGC 7026 on the nights of 1990 July 23, 26–28 and October 3–4. The observations were made with the 1.8 m Perkins Telescope of the Ohio State and Ohio Wesleyan Universities at Lowell Observatory. The arrangement consists of a Texas Instruments 4849 virtual phase CCD with format 580 × 390 pixels, mounted on a Boller and Chivens spectrograph. For both objects, the slit was oriented in an east-west position through the center of the nebula. The slit length was 5″ (3″ unvignetted), and the width was approximately 2″. Our spectra of NGC 7026 included both lobes. Our data cover the wavelength range λ3850–λ9650, which required five separate grating tilts. The spectral resolution was ~4.5 Å FWHM, sampled with 2″ pixels. In addition, we took two lower resolution spectra (~9 Å FWHM) covering the ranges λ4600–λ7100 and λ6650–λ9150 in order to connect the higher resolution data. Since we wish to measure the intensities of both strong and weak features, it was essential to ensure linearity of the detector. Tests have show that the device is linear to within a percent provided a standard 20 ms preflash is applied. It was also necessary to obtain several exposures of different lengths at each grating tilt. This resulted in saturation of some strong lines on exposures where faint lines were present. These saturated features were noted and avoided during measurements.

In addition to our objects, we also obtained for each night several bias frames, quartz lamp flat-field exposures, FeNe calibration arcs, and twilight sky frames (or dome flats if we were unable to observe the sky). Exposures of standard stars for flux calibration were made using a 5″ slit width. The stars used were BD 40°4032, BD 28°4211, and Wolf 1346. The proximity of the two nebulae allowed us to use the same standard stars for both objects. We generally observed each of the first two stars listed for each object. However, the faintness of these stars in the red forced us to use only one of the stars per object in this region. The last star was used only for the redmost spectra.

3. DATA REDUCTIONS

3.1. *Basic Reductions*

The spectra were reduced using the standard IRAF long-slit data reduction procedures. First, the average bias was determined from the overscan region of the CCD chip and subtracted from all frames. The result of this procedure on the bias frames themselves yielded the preflash. All bias frames were medianed and the result subtracted from the remaining frames. In general, we took at least three exposures of the objects and calibration frames for each exposure length. Frames of a given exposure length were then medianed to remove the effects of cosmic rays. The pixel-to-pixel variations were removed by use of the quartz flat fields. Although our objects cover only a small portion of the total slit length, we still corrected for any possible variation in the response along the slit perpendicular to the dispersion direction. This was accomplished using the dome flats or sky exposures where available. Next, we extracted the objects, standard stars, and FeNe frames to produce one-dimensional images. For the objects, the entire nebula falling within the slit was extracted and binned together. Sky subtraction of the objects and stars was done during this step by fitting a simple polynomial to the background on either side of the object profile. We then used the FeNe spectra to calibrate the frames in wavelength. In general, wavelengths were accurate to less than 1 Å; however, there were somewhat greater errors in the red, due to a lack of lines for calibration. The wavelength correction for $\lambda \leq 4200$ Å was quite poor, with the bluemost line off by nearly 30 Å. However, since there was no difficulty in identifying the lines, and we are not concerned with any kinematic data, this does not present a problem. The data were then extinction calibrated using a standard extinction curve derived for the telescope. Since both of our objects and the standard stars were observed at very low air mass, we do not expect that this step will cause any significant errors in the final relative line intensities. Finally, the spectra were flux-calibrated using the standard stars.

The above procedure resulted in a set of one-dimensional flux- and wavelength-calibrated spectra. We measured the intensities of all observable lines using an interactive IRAF package. In cases where two or more lines were blended, each line was fitted individually by varying the input wavelength and width. Lines that were known to be blended, but in which the blend could not be resolved, were treated as a single line. In general, the deblending package works quite well, except in the case of a very weak line blended with a strong one. If a line was measured on several different exposures for a given grating tilt the final value was obtained by weighting the different measurements according to the exposure time. Finally, all measured line intensities were determined with respect to Hβ. This process involved scaling all the spectra to the bluemost spectrum containing Hβ. The scale factors were determined by comparing the strongest few lines in common between two spectral ranges, avoiding blends and lines affected by telluric absorption. The resulting intensities, relative to a value of Hβ = 100.00, are given in Table 1. Here column (1) lists the line identification, including unresolved blends, and column (2) gives the rest wavelength (or a rough value in the case of blended lines). The relative intensities are listed as I_λ for both NGC 7027 and NGC 7026.

3.2. *Extinction Corrections*

Before we can compare our observations with theory, we must first determine the amount of interstellar reddening for each object. This requires a determination of both the shape, or wavelength dependence of the extinction curve, and the total amount of extinction.

For the behavior of the extinction curve with wavelength, we have utilized the formalism of Cardelli, Clayton, & Mathis (1989). They present a simple equation for the relative amount of extinction, $A(\lambda)/A_V$, as a function of a single parameter R_V, the ratio of total to selective extinction. We use $R_V = 3.1$ for both objects.

In order to determine the total amount of extinction A_V, one would ideally like to use two lines that are widely separated in wavelength and whose intensity ratio is well known from theory. Unfortunately, although our data contain both H8 and Pa8, the former is strongly blended with He I λ3889, while the latter is strongly affected by telluric absorption (see next section). Thus, we are forced to follow the usual route and use H lines whose relative intensity is derived from recombination theory. We used a method similar to that of Osterbrock, Tran, & Veilleux (1992) and determined A_V from an average of the ratios Hβ/Hα and (Pa13 + Pa12 + Pa11)/Hγ. This choice has several advantages. First, these two ratios are complementary in that the former covers a relatively small wavelength range but is accurately measured, whereas the latter is less accurately measured but covers the largest wavelength range possible

TABLE 1

LINE INTENSITIES (RELATIVE TO Hβ = 100.00)

		NGC 7027			NGC 7026		
LINE IDENTIFICATION	WAVELENGTH (Å)	I_λ	F_λ	Percent Telluric Absorption (%)	I_λ	F_λ	Percent Telluric Absorption (%)
H8, He I	3889.0	9.72	21.53	...	11.96	23.65	...
H7, [Ne III]	3969.0	34.26	71.84	...	33.6	62.76	...
He I, He II	4026.0	1.31	2.63	...	2.27	4.13	...
[S II]	4068.6	4.57	8.87	...	3.26	5.76	...
[S II]	4076.2	1.53	2.95	...	1.35	2.37	...
Hδ, He II	4101.7	18.07	34.19	...	19.21	33.17	...
C III	4186.9	0.21	0.37	...	...	...	...
He II	4199.9	0.69	1.20	...	...	...	...
C II	4267.3	0.40	0.66	...	0.78	1.19	...
Hγ	4340.5	36.16	55.87	...	35.60	51.69	...
[O III]	4363.2	18.87	28.57	...	3.70	5.27	...
He I	4387.9	0.29	0.43	...	0.75	1.06	...
He I	4471.5	1.51	3.46	...	4.25	5.60	...
He II	4541.6	1.45	1.88	...	0.41	0.51	...
Mg I	4571.1	0.56	0.71	...	...	...	...
N III	4634.1	1.43	1.71	...	1.26	1.47	...
N III	4640.6	2.97	3.54	...	2.82	3.27	...
C III	4647.4	0.67	0.79	...	1.01	1.17	...
C IV	4658.3	0.72	0.85	...	0.50	0.57	...
He II	4685.7	43.03	49.40	...	13.66	15.38	...
[Ar IV]	4711.3	3.49	2.92	...	2.67	2.96	...
[Ne IV]	4725.0	1.58	1.76	...	...	...	...
[Ar IV]	4740.2	8.34	9.17	...	2.54	2.75	...
Hβ	4861.3	100.00	100.00	...	100.00	100.00	...
He I	4921.9	0.95	0.91	...	1.63	1.57	...
[O III]	4958.9	504.48	469.67	...	339.35	319.33	...
[O III]	5006.9	1533.83	1381.98	...	1026.75	938.45	...
?	5131.0	0.18	0.15	...	...	...	...
[Fe VI]	5145.8	0.31	0.25	...	...	...	...
[Fe VII]	5158.9	0.22	0.18	...	...	...	...
[Fe VI]	5176.4	0.27	0.22	...	...	...	...
[Ar III]	5191.8	0.37	0.30	...	...	...	...
[N I]	5200.4	0.64	0.51	...	1.47	1.21	...
[Ca V]	5309.2	0.52	0.39	...	...	...	...
[Cl IV]	5323.3	0.15	0.11	...	...	...	...
[Fe VI]	5335.2	0.25	0.18	...	...	...	...
?	5345.0	0.34	0.25	...	...	...	...
He II	5411.5	6.15	4.34	...	1.64	1.21	...
[Fe VI]	5423.9	0.22	0.15	...	...	...	...
[Fe VI]	5484.8	0.12	0.08	...	...	...	...
[Cl III]	5517.7	0.32	0.21	...	1.06	0.75	...
[Cl III]	5537.8	1.04	0.69	...	1.33	0.94	...
[O I]	5577.4	0.38	0.25	...	0.72	0.50	...
O III	5592.4	0.21	0.14	...	...	...	...
[Fe VI]	5630.9	0.15	0.09	...	...	...	...
[Fe VI]	5677.0	0.22	0.14	...	...	...	...
[Fe VII]	5721.1	0.56	0.34	2	...	...	...
[N II]	5754.6	10.20	6.11	...	3.90	2.51	...
C IV	5801.3	0.72	0.42	...	...	...	...
C IV	5812.0	0.41	0.24	...	...	...	...
He I	5875.6	18.71	10.65	2	28.02	17.29	...
He II	5913.0	0.15	0.08	10	...	...	...
He II	5932.0	0.18	0.10	28	...	...	...
He II	5953.0	0.12	0.07	...	...	...	...
He II	5977.0	0.13	0.07	12	...	...	...
He II	6004.0	0.16	0.09	3	...	...	...
He II	6037.2	0.21	0.11	...	...	...	...
He II	6074.3	0.23	0.12	...	...	...	...
[Ca V], [Fe VII]	6086.9	1.15	0.60	...	...	...	...
[K IV]	6101.8	1.01	0.53	...	...	...	...
He II	6118.3	0.27	0.14	...	...	...	...
[O I]	6300.3	28.43	13.70	...	12.22	6.54	2
He I, [S III]	6312.0	9.69	4.65	...	5.09	2.72	...

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1995ApJ...442..714K

TABLE 1—*Continued*

LINE IDENTIFICATION	WAVELENGTH (Å)	NGC 7027			NGC 7026		
		I_λ	F_λ	Percent Telluric Absorption (%)	I_λ	F_λ	Percent Telluric Absorption (%)
[O I]	6363.8	10.09	4.75	...	4.19	2.20	...
Si II	6371.4	0.44	0.21	...	...	...	...
He II	6406.4	1.06	0.49	...	...	...	...
[Ar V]	6435.1	4.56	2.09	...	...	...	...
?	6527.0	0.75	0.33	...	...	...	...
[N II]	6548.1	70.08	30.84	20	109.34	54.12	6
Hα	6562.8	665.52	291.50	...	613.17	302.30	2
[N II]	6583.4	208.16	90.34	2	320.66	156.80	2
He I	6678.2	7.28	3.05	...	10.11	4.80	...
He II	6683.3	1.01	0.42	...	0.26	0.13	...
[S II]	6716.4	4.27	1.77	...	22.66	10.63	...
[S II]	6730.8	9.93	4.08	...	37.67	17.63	...
He II	6890.9	1.44	0.56	...	...	...	...
[Ar V]	7005.7	12.22	4.55	15	...	...	...
He I	7065.3	20.34	7.40	10	14.00	5.88	...
[Ar III]	7135.8	63.67	22.54	...	76.95	32.63	...
[Ar IV]	7170.6	1.55	0.54	30	...	...	...
He II	7177.5	1.19	0.42	50	...	...	...
C II	7230.0	0.52	0.18	5	...	...	...
C II, [Ar IV]	7237.0	2.25	0.77	36	...	...	...
[Ar IV]	7262.8	1.67	0.56	23	...	...	...
He I	7281.4	2.85	0.96	20	2.35	0.92	20
[O II]	7319.9	51.17	16.94	7	8.28	3.21	18
[O II]	7330.2	42.57	14.05	13	7.94	3.06	3
[Cl IV]	7530.9	1.76	0.54	...	0.88	0.32	...
He II	7592.7	2.61	0.78	...	0.60	0.21	...
[S I]	7726.5	1.23	0.35	...	...	...	...
[Ar III]	7751.1	18.84	5.31	...	19.76	6.68	...
He I	7816.2	0.26	0.07	...	...	...	...
[P II]	7876.0	0.31	0.08	2	...	...	...
[Cl IV]	8046.1	4.74	1.21	5	2.11	0.65	2
?	8196.0	1.33	0.32	11	...	...	...
He II	8236.8	5.14	1.23	25	1.50	0.47	18
Pa28	8298.8	0.50	0.12	...	...	...	...
Pa27	8306.1	0.51	0.12	2	...	...	...
Pa26	8314.3	0.61	0.14	6	...	...	...
Pa25	8323.4	0.65	0.15	...	...	...	...
Pa24	8333.8	0.77	0.18	10	1.26	0.36	15
Pa23	8345.6	1.01	0.23	...	1.22	0.35	...
Pa22, He I, He II	8360.0	1.13	0.26	6	1.87	0.53	3
Pa21	8374.5	1.01	0.23	5	1.46	0.41	3
Pa20	8392.4	1.13	0.26	...	0.78	0.22	...
Pa19	8413.3	1.21	0.27	...	0.87	0.24	...
Pa18	8438.0	1.32	0.30	...	1.14	0.32	...
O I	8446.5	0.81	0.18	...	0.66	0.19	...
Pa17	8467.3	1.34	0.30	...	1.47	0.40	...
Pa16, [Cl III]	8502.5	1.96	0.43	...	1.52	0.42	...
Pa15	8545.4	2.79	0.61	4	1.88	0.51	...
[Cl II]	8579.0	1.74	0.38	...	1.03	0.28	...
He I	8582.0	0.61	0.13	...	0.50	0.14	...
Pa14	8598.4	3.59	0.77	...	2.66	0.71	...
Pa13	8665.0	4.62	0.97	...	3.32	0.87	...
[C I]	8727.0	1.02	0.21	...	...	...	...
Pa12	8750.5	4.77	0.98	...	3.80	0.99	...
Pa11	8862.8	6.64	1.33	...	4.89	1.24	2
Pa10	9014.9	9.43	1.83	5	7.38	1.82	35
[S III]	9069.0	126.02	24.20	37	231.69	56.30	25
Pa9	9229.0	14.46	2.69	10	11.52	2.73	8
[S III]	9530.9	572.90	100.83	30	506.71	114.52	30
Pa8	9546.0	21.35	3.76	30	7.70	1.73	30

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from our data (the three Paschen lines redward of Pa11 all have nonnegligible telluric absorption, while the Balmer lines blueward of Hγ have potential blending problems). Second, Mathis (1983) has shown that for dusty nebulae (as NGC 7027 is), determining the reddening by using Hβ/Hα alone could lead to serious errors for $\lambda \geq 8000$ Å. He attributes this to the differing dust albedos at the wavelengths of these two lines. The Paschen-line to Hγ ratio should be only slightly affected by this phenomenon. In any case, since the He lines of interest to us all have wavelengths less than 8000 Å, this should not be a concern.

We have determined the theoretical intensities of the Hβ/Hα and (Pa13 + Pa12 + Pa11)/Hγ ratios from the data of Hummer & Storey (1987) by interpolating logarithmically in both temperature and density. The precise values of n_e and T_e used are not critical to the final result, as these ratios are not strongly dependent on these parameters. Table 2 shows the results of this method. We note that the final average result for NGC 7027 of $A_V = 2.59$ is lower than that derived by other investigators (e.g., $A_V = 3$; Atherton et al. 1979). This discrepancy may reflect the uncertainty involved in connecting our different wavelength ranges. We will use the value derived here since it is self-consistent with our data. In any event, our final, reddening-corrected line intensities agree well with other observations of this object. These intensities are listed as F_λ in Table 1, again relative to Hβ = 100.00.

3.3. *Corrections for Telluric Absorption*

An important effect in the red and near-infrared part of the spectrum is absoption by molecules (primarily H_2O) in the Earth's atmosphere. This effect manifests itself in the presence of the familiar absorption bands in low-resolution spectra. However, in reality these and other bands not noticeable at low resolution consist of dozens of sharp, individual lines. If one of these coincides with a spectral line in the object, the intensity in the spectral line can be significantly reduced. Although standard corrections are often applied to spectra to remove the absorption *bands*, these corrections are made at low resolution and thus do not correct for the effect of individual *lines*. Thus it is essential to determine whether a given spectral line is affected by this phenomenon, and to estimate the degree of absorption.

TABLE 2

DETERMINATION OF AMOUNT OF EXTINCTION

Line Ratios	Observed	Intrinsic	A_V
NGC 7027			
$F(H\alpha)/F(H\beta)$	6.65	2.78	2.74
$F(Pa11)/F(H\gamma)$	0.1836	0.0280	2.37
$F(Pa12)/F(H\gamma)$	0.1319	0.0219	2.31
$F(Pa13)/F(H\gamma)$	0.1278	0.0174	2.60
$F(Pa11 + Pa12 + Pa13)/F(H\gamma)$	Mean	...	2.43
Final average			2.59
NGC 7026			
$F(H\alpha)/F(H\beta)$	6.13	2.85	2.40
$F(Pa11)/F(H\gamma)$	0.1402	0.0294	1.98
$F(Pa12)/F(H\gamma)$	0.1067	0.0226	2.00
$F(Pa13)/F(H\gamma)$	0.0933	0.0178	2.15
$F(Pa11 + Pa12 + Pa13)/F(H\gamma)$	Mean	...	2.04
Final average			2.22

Our technique is essentially that of Kingdon & Ferland (1991, hereafter KF), and the reader is referred to that paper for a more detailed discussion. For each spectral line measured in our objects, we determined the rest wavelengths. Then, based on the date of observation, and the object's coordinates and heliocentric radial velocity, we computed the geocentrically shifted wavelengths. We then searched for all significant telluric lines in the vicinity of each line using the high-resolution solar spectra of Delbouille, Roland, & Neven (1973) and the compilation by Park et al. (1981).

The optical depth in a telluric line is given by (cf. Goody 1964)

$$\tau_\lambda = \frac{Sa\Gamma}{2\pi[(\Delta\lambda)^2 + \Gamma^2/4]} , \tag{1}$$

where S is the line strength (in units of Å/g cm^2), a is the total column density of water vapor, Γ is the full width at half-maximum (FWHM), and $\Delta\lambda$ is the displacement from line center. We discuss the determination of these values below.

The line strength S was determined from Park et al. (1981) by scaling their values (expressed in different units) to those determined by KF. The column density a is the product of the column density of precipitable water vapor and the air mass. For the first factor, we used monthly means of data taken from Kitt Peak (cf. Wallace et al. 1984 and Wallace & Livingston 1984), which should be reasonably similar to the conditions at the Perkins Telescope in Flagstaff. The air masses were taken from the observing logs. Since very little data exist for the telluric line FWHM, we have assumed a reasonable value of $\Gamma = 0.134$ for all lines (cf. Rothman et al. 1987).

Next it is necessary to determine the object line profiles. Due to the well-known expansion effect, lines in PNs are split into two components. Although the amount of splitting differs for each ion, with the higher stages of ionization showing less splitting, we used "average" expansion velocities (usually determined from [O III] lines) for each object. We took $V_{\rm exp}$ = 18 km s^{-1} for NGC 7027 and $V_{\rm exp}$ = 42 km s^{-1} for NGC 7026 from the compilation by Acker et al. (1982). Each line was then split into two components from its geocentrically shifted position. Both components were assumed to be thermally broadened Gaussians, with the total flux divided equally between the two. No account was made for fine structure (i.e. doublets, triplets, etc., were considered to be single lines). This essentially corresponds to model 1 of KF.

The amount of absorption due to a single telluric line is simply

$$A = \int_{-\infty}^{\infty} P(\lambda)(1 - e^{-\tau_\lambda})d\lambda , \tag{2}$$

where $P(\lambda)$ is the normalized spectral line profile. For each spectral line in our objects, we calculated this integral for all nearby telluric lines, then summed the results. The percentage of telluric absorption, if different from zero, is given in Table 1 for both objects.

As discussed in KF, we do not expect that our corrections are of very high accuracy due to lack of data for the telluric lines. However, the values given in Table 1 are useful for indicating which lines are affected by telluric absorption, and the relative importance of this effect. One might consider making an estimate of the accuracy by examining a line such as Pa8 that is affected. By using recombination theory, one could determine an intensity by scaling from other, unaffected lines.

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In theory, comparing this scaled value and the observed value could empirically determine the amount of absorption. In practice, however, the observational uncertainties are such as to render this method useless.

Finally, we wish to emphasize again the importance of this effect for narrow-lined objects. In a study of the Orion nebula, Osterbrock, Shaw, & Veilleux (1990) noted that Pa10 was anomalously weaker than Pa11, but attributed this to some unknown observational error. Although our data do not show such an effect due to the observational uncertainties, our calculations show that Pa10 should be strongly affected by telluric absorption, whereas Pa11 is only weakly so. Any nebular diagnostics using lines that are strongly affected by this phenomenon must therefore be viewed with an appropriate amount of skepticism.

4. CALCULATIONS

In this section we shall determine the accuracy of the standard C/R correction factors by comparing our observed He I line intensities with those predicted by theory. We detail our calculations step by step below.

4.1. *Physical Parameters*

In order to calculate both the recombination intensities and the C/R correction factors, it is necessary to know both the temperature and density in the He^+ zone in which these lines are produced. We begin our discussion with the density.

There exist several diagnostic line ratios in the optical for the determination of electron density, n_e. A useful paper showing the variation of n_e for several line ratios is Stanghellini & Kaler (1989, hereafter SK). These authors also give the range of applicability for the various line ratios. Of the four line ratios discussed in this paper, we have three present in our data: [Cl III] λ5517–5537, [S II] λ6717–6730, and [Ar IV] λ4711–4740. For NGC 7027, our [Cl III] ratio comes very close to the upper density limit for this ion ($n_e \sim 8 \times 10^4$) and is thus unreliable (this fact was noted by SK). This is also the case for the [S II] ratio. We are left then with the [Ar IV] ratio. As mentioned by SK, this ratio is very useful for high-density PNs. Our data imply $n_e \sim 2.5 \times 10^4$. Although this value is in reasonable agreement with other determinations for this nebula listed in SK, we consider it to be a lower limit for the actual density due to blending of the [Ar IV] λ4711 line with He I λ4713 and [Ne IV] λ4715. The observations of Keyes et al. (1990) shows that these two lines have approximately 40% of the total intensity of the blend. If we modify 4711 for this effect, we obtain $n_e \sim 5.5 \times 10^4$. This is in good agreement with the densities derived for the He^+ zone by Keyes, Aller, & Feibelman (1990) and Middlemass (1990). We shall use this density in our subsequent calculations. We note here that due to the very high density of this object, the collisional effects are almost independent of density. For example, an increase in our derived density by a factor of 2 would result in only a ∼5% increase in the collisional contribution to all line intensities.

For NGC 7026, all three diagnostic ratios give reliable results. Both the [Cl II] ratio and the [S II] ratio give $n_e \sim 4 \times 10^3$, while the [Ar IV] ratio gives a very similar result of $n_e \sim 3 \times 10^3$. These results compare well with other listed values. We shall use the [S II] and [Cl II] value.

The temperature in the He^+ zone, $T_e(He^+)$, can be determined from $T_e(He^+) = T_e(O^{++})$, where the latter temperature is that in the zone producing the O III lines. Kaler (1986) provides a simple formula for determining this temperature, based on atomic data from the compilation by Mendoza (1983). This formula is a function of three parameters, T_e, n_e, and the ratio of the sum of [O III] λ5007 and λ4959 to [O III] λ4363. However, the results are only weakly dependent on the values of the first two parameters, and we thus use $T_e = 10^4$ and the n_e values determined above in the following.

For NGC 7027, using our observed [O III] ratio, we obtain $T_e \sim 14{,}000$. This value agrees to within ∼5% of the [O III] temperatures derived from the observations of Keyes et al. (1990), Middlemass (1990), Barker (1978), and Keyes et al. (1976). We thus adopt this value. For NGC 7026, the [O III] lines give $T_e \sim 9500$.

In summary, our adopted parameters are $n_e = 5.5 \times 10^4$ and $T_e = 14{,}000$ for NGC 7027 and $n_e = 4 \times 10^3$ and $T_e = 9500$ for NGC 7026.

4.2. *Observational Data and Errors*

We are now ready to begin with our calculation of the depopulation factor γ. We shall consider nine He I lines for this purpose. These lines are λ3889, λ4026, λ4387, λ4471, λ4922, λ5876, λ6678, λ7065, and λ7281. We have already listed the intensities of these lines relative to Hβ in Table 1. In the following, we shall attempt to determine the various errors in these intensities.

4.2.1. *Scaling Errors*

Unfortunately, it is extremely difficult to accurately determine errors in these relative intensities, since small errors can occur in virtually every step of the data reductions. We will consider two sources of error here. First, if a line was measured on more than one exposure, we determined an error in its intensity by comparing the intensity on the different exposures. Second, we determined errors due to the scaling described above by examining the intrinsic error in each scaling (done by comparing the scale factors determined from each strong line used in the calculation of the average scale factor for that particular grating tilt), and then propagating these errors through each subsequent spectral range. For the wavelength ranges λ5007–λ6118, λ6300–λ7281, λ7320–λ8467, and λ8502–λ9650, these scaling errors are 8%, 12%, 15%, and 16% for NGC 7027 and 5%, 8%, 10%, and 20% for NGC 7026.

4.2.2. *Reddening Errors*

We have determined the errors in our dereddening procedure by considering the observational uncertainties in the H lines used in our calculation of A_V in the last section. These errors were then propagated throughout the reddening computations. In general, these errors amounted to roughly 10% on average. The percentage error is smaller for lines near the reference Hβ, and larger far away from it.

4.2.3. *Removal of Blends*

Two of the lines that we wish to consider are strongly blended with other lines: λ3889 with H8 λ3889, and λ4026 with He II λ4026. Our deblending technique involved determining the intensity of H8 and He II λ4026 by using our observations and recombination theory. For H8, we used the observed intensities of Hδ, Hγ, Hβ, and Hα. Using the recombination intensities of Hummer & Storey (1987), we derived an average line intensity for the ratio H8/Hβ. This intensity, which amounts to roughly 50% of the total intensity of the blend for both nebulae, was then subtracted from the blend to yield He I λ3889 relative to Hβ.

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TABLE 3

DETERMINATION OF γ FOR NGC 7027

Line ID	Observed	C/R (Theoretical)	Recombination	Self-Absorption	γ
3889 ($2\,^3S$–$3\,^3P$)	10.60	0.57	9.43	0.89	0.63
	(2.53)	(0.13)	(0.29)	(0.25)	(1.17)
4026 ($2\,^3P$–$5\,^3D$)	2.23	0.19	1.80	1.00	8.00
	(0.25)	(0.07)	(0.01)	(0.02)	(24.45)
4387 ($2\,^1P$–$5\,^1D$)	0.47	0.10	0.47	1.00	0.00
	(0.02)	(0.03)	(0.002)	(0.01)	[a]
4471 ($2\,^3P$–$4\,^3D$)	3.80	0.30	3.73	1.00	0.12
	(0.15)	(0.11)	(0.01)	(0.01)	(0.25)
4922 ($2\,^1P$–$4\,^1D$)	1.00	0.13	1.00	1.01	...
	(0.00)	(0.04)	(0.00)	(0.01)	...
5876 ($2\,^3P$–$3\,^3D$)	11.94	0.52	9.89	1.01	0.54
	(1.77)	(0.16)	(0.11)	(0.02)	(0.55)
6678 ($2\,^1P$–$3\,^1D$)	3.35	0.19	2.80	1.01	4.50
	(0.55)	(0.05)	(0.03)	(0.02)	(5.48)
7065 ($2\,^3P$–$3\,^3S$)	9.04	2.41	2.02	1.26	1.31
	(1.64)	(0.44)	(0.10)	(0.80)	(1.26)
7281 ($2\,^1P$–$3\,^1S$)	1.32	0.87	0.63	...	...
	(0.25)	(0.15)	(0.03)	...	...

NOTE.—Errors for each value appear in parentheses below.

[a] Value indeterminate (see text).

Likewise, in order to eliminate the He II λ4026 line from the He I line at this wavelength, we used the He II lines λ4199 (for NGC 7027 only), λ4541, λ4686, and λ5411. We again made use of the relative recombination intensities by Hummer & Storey (1987). The resulting average intensity was roughly 25% of the blend for NGC 7027, but only 4% of the blend for NGC 7026, due to its lower abundance of He II.

Our errors were determined by propagating the observational uncertainties in the lines used in determining the deblending. As can be expected, the deblending process increased the percentage errors in both of these lines. We should note that we did *not* consider the errors in the recombination intensities. All our calculations assumed $n_e = 10^4$ and $T_e = 10^4$. The recombination relative intensities change by only a few percent over the range of interest in these parameters. These errors are sufficiently small compared to the total observational errors that they can safely be neglected.

4.2.4. *Final Observational Intensities and Errors*

In order to examine the He I lines without resorting to a photoionization model, it is necessary to express their intensities relative to a given He I line. We choose the line λ4922 as our reference line. This line has the advantage of being reasonably well measured and also is expected to have a very small collisional enhancement.

In Tables 3 and 4 we list the final intensities of the He I lines, relative to $I(\lambda4922) = 1.00$, for NGC 7027 and NGC 7026, respectively. In both tables column (1) gives the wavelength and transition for each line. Column (2) gives the observed intensities, along with their errors. Most of the errors are at the

TABLE 4

DETERMINATION OF γ FOR NGC 7026

Line ID	Observed	C/R (Theoretical)	Recombination	Self-Absorption	γ
3889 ($2\,^3S$–$3\,^3P$)	7.65	0.13	8.36	0.85	0.73
	(1.35)	(0.07)	(0.22)	(0.14)	(2.41)
4026 ($2\,^3P$–$5\,^3D$)	2.53	0.02	1.76	1.00	[a]
	(0.22)	(0.02)	(0.01)	(0.00)	[a]
4387 ($2\,^1P$–$5\,^1D$)	0.68	0.01	0.46	1.00	−24.00
	(0.04)	(0.01)	(0.002)	(0.01)	(36.28)
4471 ($2\,^3P$–$4\,^3D$)	3.57	0.04	3.70	1.00	−2.00
	(0.20)	(0.03)	(0.00)	(0.00)	(4.72)
4922 ($2\,^1P$–$4\,^1D$)	1.00	0.02	1.00	1.01	...
	(0.00)	(0.02)	(0.00)	(0.01)	...
5876 ($2\,^3P$–$3\,^3D$)	11.01	0.08	10.26	1.01	1.00
	(1.09)	(0.06)	(0.14)	(0.01)	(2.09)
6678 ($2\,^1P$–$3\,^1D$)	3.06	0.04	2.92	1.01	2.00
	(0.38)	(0.02)	(0.04)	(0.02)	(7.16)
7065 ($2\,^1P$–$3\,^3S$)	3.75	0.68	1.69	1.42	0.86
	(0.59)	(0.34)	(0.06)	(0.42)	(0.93)
7281 ($2\,^1P$–$3\,^1S$)	0.73	0.25	0.53	...	...
	(0.17)	(0.12)	(0.02)	...	...

NOTE.—Errors for each value appear in parentheses below.

[a] Value indeterminate (see text).

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10% level. The intensities of λ5876, λ7065, and λ7281 in NGC 7027 and of λ7281 in NGC 7026 have been tentatively corrected for telluric absorption. No account has been made of this correction in the listed errors.

4.3. *Theoretical C/R Factors*

In this section we will derive theoretical C/R factors to compare with the empirical factors calculated above. Since this will involve the calculation of new formulae, we wish to first briefly discuss their derivation. More detailed explanations are given by Clegg (1987) and PTP1.

For any given line, the ratio of the collisional component to that arising from recombination is given by

$$\frac{C}{R} = \frac{n_{2\,{}^3S}\, k_{\rm eff}}{n_{\rm He}^{+}\, \alpha_{\rm eff}} \qquad (3)$$

where $n_{2\,{}^3S}$ and $n_{\rm He^+}$ are the densities of the $2\,{}^3S$ state and He$^+$, respectively, $\alpha_{\rm eff}$ is the effective recombination coefficient for the line, and $k_{\rm eff}$ is the effective collisional rate coefficient, including the appropriate branching ratios. Note that for each line, $k_{\rm eff}$ may consist of a series of terms.

If we neglect photoionization of $2\,{}^3S$ (see Clegg & Harrington 1989 for a discussion of this effect), the ratio of the densities in equation (3) can be written

$$\frac{n_{2\,{}^3S}}{n_{\rm He^+}} = \frac{n_e \alpha_B}{A_{21} + n_e q_{\rm tot}}\,, \qquad (4)$$

where n_e is the electron density, α_B is recombination coefficient to all triplet levels, and A_{21} is the radiative decay rate from $2\,{}^3S$ to $1\,{}^1S$. The term $q_{\rm tot}$ consists of collisional transfer from $2\,{}^3S$ to all singlet levels plus collisional ionization.

We used $A_{21} = 1.13 \times 10^{-4}$ s^{-1} (Hata & Grant 1981). We then used power-law fits to the other parameters, which are generally valid over the range $t_4 = 0.8$–2.0 (Here and subsequently, we define $t_4 = T/10{,}000$). For α_B, using the tables in Osterbrock (1989), we obtained $\alpha_B = 2.03 \times 10^{-13} t_4^{-0.69}$ cm^3 s^{-1}. Values for $\alpha_{\rm eff}$ were taken from Smits (1994). We obtained the collisional ionization part of $q_{\rm tot}$ from Table 1 of Clegg (1987). Substituting the appropriate values into equation (4) yields

$$\frac{n_{2\,{}^3S}}{n_{\rm He^+}} = \frac{5.62 \times 10^{-6} t_4^{-1.19}}{1 + 3130 t_4^{-0.5} n_e^{-1}}\,. \qquad (5)$$

As mentioned previously, it can be seen from this equation that for $n_e \gg 3000$, the ratio has only a very weak dependence on density.

Recently, Sawey, & Berrington (1993) have completed a 29-state quantal calculation of He I, including states up to $n = 5$. We have made power-law fits to the collision strengths from their data. Analogously to Clegg (1987), we used the full rates up to $n = 4$, but took 50% of the values for $n = 5$. The new data have allowed us to improve upon previously calculated formulae, such as those of Clegg (1987) and PTP1, as well as to derive new C/R factors for λ4026, λ4387, λ4922, and λ7281.

We present the new C/R formulae below. In order to calculate the appropriate branching ratios, we have made use of transition probabilities from the Opacity Project (cf. Seaton 1987). The formulae contain only significant terms; in general, terms comprising less than 1% of the total were ignored. As mentioned by Clegg (1987), these formulae are only strictly correct in objects for which photoionization of the $2\,{}^3S$ state is negligible. In all of the formulae, the denominator D is equal to $(1 + 3130 t_4^{-0.50} n_e^{-1})$.

For λ3889, we used the collision terms to $3\,{}^3P$, $4\,{}^3S$, $4\,{}^3D$, $5\,{}^3S$, and $5\,{}^3D$. This gives

$$\begin{aligned}\frac{C}{R}(\lambda3889) = (&9.34 t_4^{-0.92} e^{-3.699/t_4} \\ &+ 1.64 t_4^{-0.79} e^{-4.379/t_4} + 0.83 t_4^{-0.40} e^{-4.545/t_4} \\ &+ 0.51 t_4^{-1.05} e^{-4.818/t_4} + 0.39 t_4^{-0.36} e^{-4.900/t_4})/D\,. \qquad (6)\end{aligned}$$

For λ4026, only the $5\,{}^3D$ term contributes, yielding

$$\frac{C}{R}(\lambda4026) = 6.92 t_4^{-0.45} e^{-4.900/t_4}/D\,. \qquad (7)$$

Likewise, for λ4387, only the $5\,{}^1D$ term is appreciable:

$$\frac{C}{R}(\lambda4387) = 4.43 t_4^{-0.62} e^{-4.900/t_4}/D\,. \qquad (8)$$

For λ4471, we used the $4\,{}^3D$ term, along with the new $5\,{}^3P$ and $5\,{}^3F$ terms to obtain

$$\begin{aligned}\frac{C}{R}(\lambda4471) = (&6.95 t_4^{0.15} e^{-4.545/t_4} + 0.22 t_4^{-0.55} e^{-4.884/t_4} \\ &+ 0.98 t_4^{-0.45} e^{-4.901/t_4})/D\,. \qquad (9)\end{aligned}$$

For λ4922, we used the $4\,{}^1D$ and $5\,{}^1F$ terms to obtain

$$\frac{C}{R}(\lambda4922) = (3.86 t_4^{-0.36} e^{-4.545/t_4} + 0.32 t_4^{-0.77} e^{-4.901/t_4})/D\,. \qquad (10)$$

For λ5876, we consider the $3\,{}^3D$, $4\,{}^3F$, and $5\,{}^3F$ terms which yielded

$$\begin{aligned}\frac{C}{R}(\lambda5876) = (&6.78 t_4^{0.07} e^{-3.776/t_4} + 1.67 t_4^{-0.15} e^{-4.545/t_4} \\ &+ 0.60 t_4^{-0.34} e^{-4.901/t_4})/D\,. \qquad (11)\end{aligned}$$

Analogously, for λ6678, only the $3\,{}^1D$, $4\,{}^1F$, and $5\,{}^1F$ terms were appreciable:

$$\begin{aligned}\frac{C}{R}(\lambda6678) = (&3.15 t_4^{-0.54} e^{-3.776/t_4} + 0.51 t_4^{-0.51} e^{-4.545/t_4} \\ &+ 0.20 t_4^{-0.66} e^{-4.901/t_4})/D\,. \qquad (12)\end{aligned}$$

For λ7065, we used only the $3\,{}^3S$ and $3\,{}^3P$ terms to obtain

$$\frac{C}{R}(\lambda7065) = (38.09 t_4^{-1.09} e^{-3.364/t_4} + 2.80 t_4^{-1.06} e^{-3.699/t_4})/D\,. \qquad (13)$$

Finally, for λ7281, only the $3\,{}^1S$ term was appreciable, giving

$$\frac{C}{R}(\lambda7281) = 18.78 t_4^{-1.36} e^{-3.598/t_4}/D\,. \qquad (14)$$

We list the theoretical C/R factors and their uncertainties in column (3) of Tables 3 and 4. The uncertainties in the C/R factors were obtained by considering how a 50% change in n_e and a 10% change in T_e would affect the results. These percentages were determined by comparing values of n_e and T_e as determined by other observers for these objects. An inspection

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of these values shows that the uncertainties can be rather large. In particular, the percentage uncertainties are significantly greater for NGC 7026 than for NGC 7027. This is due to the fact that, as previously mentioned, for high-density objects such as NGC 7027, the collisional effects are almost independent of density. Thus, the uncertainties in C/R for NGC 7026 reflect the uncertainties in both n_e and T_e, while those for NGC 7027 only reflect the uncertainties in T_e.

4.4. *Recombination Intensities*

Since the total observed intensity of each line we are considering is a sum of the recombination plus collisional component, we must determine the former in order to measure C/R. For this we used the data of Smits (1994) for all lines, which is an improvement over the Smits (1991) work. With the exception of lines in the series $2\,^3P$–$n\,^3S$ (Smits 1991), the data of Smits are in excellent agreement with that of Brocklehurst (1972). It was necessary to interpolate these tables to our adopted densities and temperatures. The interpolation in the density was done linearly, as the line intensities are not strongly dependent on this parameter. For the temperature, we assumed an equation of the form $I(n_e, T_e, n', n) = A(n_e, n', n)T_4^{\beta}$, where n' and n denote the upper and lower levels of the transition, and A and β are parameters to be solved for. Note that we assumed case B for the singlet lines.

We determined errors in the recombination intensities analogously with those of the C/R factors, that is, by considering how a 50% change in n_e and a 10% change in T_e would change our results. In general, the errors are less than a few percent, although the errors in λ7065 and λ7281 are somewhat larger due to a stronger temperature dependence. Our results are given in column (4) of Tables 3 and 4.

4.5. *Correction for Self-Absorption*

Another effect of the metastability of the $2\,^3S$ level is that lines resulting from transitions $2\,^3S$–$n\,^3P$ can have large optical depths. If such lines are scattered many times, it is possible for them to be converted to other lines via resonance fluorescence. A well-known example is λ3889 ($2\,^3S$–$3\,^3P$), which can be converted to an infrared line at 4.3 μm ($3\,^3S$–$3\,^3P$) plus λ7065. Thus λ3889 is weakened as a result of this process, while λ7065 is strengthened. Similar processes resulting from absorption of higher $2\,^3S$–$n\,^3P$ lines can produce lesser effects in other He I lines such as λ5876.

The usual method of correcting line intensities for this effect is to use tables to determine $\tau(\lambda3889)$, the optical depth in λ3889, based on line intensity ratios. One then uses this value and the tables to correct all lines by comparing their intensity at this optical depth to that for $\tau(\lambda3889) = 0.0$.

One set of tables commonly used are those of Robbins (1968). He lists several line intensity ratios as a function of $\tau(\lambda3889)$ and $V_{\rm exp}/V_{\rm ther}$, the nebular expansion velocity divided by the thermal velocity, for $n_e = 10^4$ cm^{-3} and $T_e = 10^4$ and 2×10^4 K. Unfortunately, these tables are rather old, but the values for $\tau(\lambda3889) = 0.0$ are reasonably close to those given by Smits (1994).

At this point, we are faced with a major problem. The Robbins tables show how the *recombination* line intensity ratios vary, whereas the observed line ratios contain both *recombination plus collisional* components. In order to use the tables, then, one would have to divide each line by a factor 1 + C/R. However, it is the C/R factors that we are attempting to verify. Any assumption for these values would result in a circular argument. To make matters worse, the lines that are most affected by self-absorption and are therefore the best to measure this effect are also strongly collisionally enhanced. In theory, since the "true" C/R factors are simply γ times the theoretical values, if two lines have the same value for C/R, then the effect of collisions would effectively drop out of the calculations. Unfortunately, as Tables 3 and 4 show, the only line ratios which satisfy this requirement are useless for measuring the self-absorption.

We are thus forced to try an alternate approach. For any observed line ratio, $I^1_{\rm obs}/I^2_{\rm obs}$, the combination ratio, which is used in the Robbins tables, can be written as

$$\frac{I^1_{\rm rec}}{I^2_{\rm rec}} = \frac{I^1_{\rm obs}}{I^2_{\rm obs}} \times \frac{1 + \gamma(C/R)_2}{1 + \gamma(C/R)_1}\,. \tag{15}$$

Therefore, by using two separate line ratios, we can determine what value of γ will result in the same measured optical depth $\tau(\lambda3889)$. This is essentially the method used by PTP2.

For NGC 7027, we took $V_{\rm exp}/V_{\rm ther} = 3$ and interpolated to our adopted T_e and n_e. Although the line ratios λ3889/λ4471 and λ7065/λ4471 are the preferred choice for measuring self-absorption, we have avoided the latter because of the uncertain telluric correction. Although this correction is relatively small, λ7065 depends strongly on optical depth, so that even a minor error in the intensity can result in a substantial error in the derived optical depth and corresponding self-absorption correction. We therefore choose λ3889/λ4471 and λ3889/λ5876. Since λ5876 depend only weakly on optical depth, the 2% telluric correction should have essentially no effect. These two line ratios predicted an optical depth of $\tau(\lambda3889) = 3.86 \pm 10.93$ for a value of the depopulation factor γ of 0.85 ± 0.68. This optical depth was then used to correct all triplet lines.

For NGC 7026, we used $V_{\rm exp}/V_{\rm ther} = 5$. In this case, the absence of telluric absorption in λ7065 allowed us to use λ3889/λ4471 and λ7065/λ4471 as our two ratios. These gave $\tau(\lambda3889) = 7.83 \pm 8.33$ for $\gamma = 0.89 \pm 0.34$. Again, the mean value was used to correct all triplet lines.

We determined the errors in these self-absorption corrections in several steps. First, we combined the observational uncertainties in the lines and the uncertainties in the C/R factors to derive the errors in the λ3889/λ4471, λ3889/λ5876, and λ7065/λ4471 ratios used to determine $\tau(\lambda3889)$. Second, we used the tables to translate these uncertainties into uncertainties in the adopted mean optical depths. Finally, we again used the tables to translate these errors into uncertainties in resulting corrections. Although the uncertainties in $\tau(\lambda3889)$ obtained by this method are quite substantial, the weakness of the self-absorption effect on most lines ensures that the resulting errors in the correction factors are relatively small.

Self-absorption is also present in the singlet lines. This effect is due to absorptions in $1\,^1S$–$n\,^1P$, in which the upper level can decay to other states, thus enhancing the lines formed by those transitions. Robbins & Bernat (1973) have compiled a similar set of tables for this effect, listing line intensity ratios as a function of $V_{\rm exp}/V_{\rm ther}$ and the optical depth in λ584 ($1\,^1S$–$2\,^1P$). We are again faced with the same problem as with the triplets, that is, the self-absorption effects are coupled with the collisional effects. Unfortunately, since λ7281 is the only observed line for which the self-absorption is appreciable, and this line is strongly affected by telluric absorption in both objects, we have no accurate way to measure the amount of self-absorption. Since Robbins & Bernat (1973) state that our remaining singlet lines should show almost no self-absorption effects, we discard λ7281 from our calculations and adopt "reasonable" corrections for the other singlet lines.

The self-absorption correction factors and their accompanying uncertainties are listed in column (5) of Tables 3 and 4. These corrections are to be multiplied by the recombination intensities, or divided into the observational intensities.

Although our measurement of self-absorption in the triplets has allowed us to determine γ, we will make use of these corrections to determine γ individually for each line in the next section.

4.6. *Depopulation of the* $2\,^3S$ *State*

We are now ready to determine whether the $2\,^3S$ level is depopulated and to what extent by deriving the depopulation factor γ from our data. First, we divide the observed intensity ratios by the recombination intensity ratios corrected for self-absorption. This gives us, for each line ratio, an equation of the form

$$\frac{1+\gamma(C/R)_1}{1+\gamma(C/R)_2} = \text{const} \qquad (16)$$

from which γ is readily determined.

The results, along with the accompanying uncertainties, are listed in column (6) of Tables 3 and 4. In two cases, the value or its associated error is listed as indeterminate. For the λ4387 line for NGC 7027, the error is undetermined due to the zero value derived for γ. For the λ4026 line in NGC 7026, the predicted C/R factor is equal to that of the λ4922 reference line. Thus, nothing whatsoever can be said about the collisional effect for this line. Obviously, negative values have no meaning and only reflect the uncertainties. We shall discuss these values and the anomalously high values in the next section. Note that the value of γ derived from λ4026 and λ4387 shows the largest discrepancy with theory for both objects and has the largest percentage errors for NGC 7027. These lines suffer from several errors: they are the weakest lines included in the derivation, they have the smallest predicted C/R values, and the closeness of their C/R values with that of the reference line is also a problem (see the next section). Furthermore, the theoretical C/R values for these lines are especially uncertain, since the only available collisional rates involve the uncertain $n = 5$ levels. It is expected that collisions to the $n = 6$ levels could make a significant increase to the C/R values for these lines. We thus reject λ4026 and λ4387 from our determination of an average value of γ. If we do a simple average of the remaining values, we obtain $\gamma = 1.42 \pm 1.16$ for NGC 7027 and $\gamma = 0.52 \pm 1.84$ for NGC 7026. The averages obtained by this and other methods are listed in Table 5 for convenience. For NGC 7026, we also list the results obtained if λ4471, whose predicted γ is negative, is excluded from the averaging. A more realistic average can be calculated by taking into account the individual uncertainties in the lines. We calculate averages in which the individual γ values are weighted in inverse proportion to their errors. These results are listed as "Weighted average 1" in Table 5. Another major source of error involves lines in which the collision enhancement is small, and the C/R value is close to that of our reference line λ4922. In order to correct for this effect, we weight each line by a factor discussed in the next section. These results are listed as "Weighted average 2" in Table 5. Finally, we weight each line by a combination of the two error sources. We choose this "doubly weighted" average as our best result, which gives $\gamma = 0.92 \pm 0.60$ for NGC 7027 and $\gamma = 0.70 \pm 0.87$ (or 0.92 ± 0.85, excluding λ4471) for NGC 7026.

TABLE 5

AVERAGE VALUES OF γ

Parameter	Value
NGC 7027	
Self-absorption	0.85 ± 0.68
Straight average	1.42 ± 1.16
Weighted average 1	1.55 ± 1.23
Weighted average 2	0.82 ± 0.58
Weighted average 3	0.92 ± 0.60
NGC 7026	
Self-absorption	0.89 ± 0.34
Straight average	0.52 ± 1.84
	1.15 ± 1.97[a]
Weighted average 1	0.50 ± 1.33
	1.03 ± 1.26[a]
Weighted average 2	0.66 ± 1.14
	0.96 ± 1.15[a]
Weighted average 3	0.70 ± 0.87
	0.92 ± 0.85[a]

[a] Average excluding λ4471.

5. DISCUSSION AND CONCLUSIONS

A cursory glance at column (6) of Tables 3 and 4 reveals both a large scatter in the results and appreciable uncertainties. We shall discuss the reasons for this below, beginning first with the anomalous values of γ.

It is clear from an examination of equation (16) that when $(C/R)_1$ and $(C/R)_2$ are very close, the value of γ is poorly determined. Indeed, in the limit in which $(C/R)_1$ equals $(C/R)_2$, the right-hand side of the equation goes to 1 and we can say nothing about γ. This is the situation for λ4026 in NGC 7026. If we solve equation (16) for γ, we get

$$\gamma = \frac{c-1}{(C/R)_1 - c(C/R)_2}, \qquad (17)$$

where c denotes the constant. It is clear that for certain values of $(C/R)_1$, $(C/R)_2$, and c, the derived γ can be negative. In practice, when $(C/R)_1$ and $(C/R)_2$ are very close, this can occur for very slight observational errors in determining c. This is the case for λ4387 and λ4471 in NGC 7026. Further, from equation (17) it can be seen that as $(C/R)_1/(C/R)_2$ approaches c, γ goes asymptotically to $\pm\infty$. Again, in practice, this effect is more pronounced for $(C/R)_1$ and $(C/R)_2$ very close in value. This effect results in the anomalously large (both positive and negative) values in column (6) of Tables 3 and 4. This is one of the main reasons that we chose λ4922 as a reference line rather than a stronger, but more collisionally affected line such as λ5876. Since the C/R value for λ4922 is small, the above effect will only affect lines with similarly small collisional enhancement. These lines will have greater intrinsic error anyway, as discussed below. Had we chosen the more commonly used λ4471 as our reference line, stronger lines such as λ5876 and λ3889 would have been overestimated due to this problem. Although one obvious way to avoid this effect would be to use λ7065 as a reference line, since its C/R value is significantly above the other lines, the problems of uncertain self-absorption and telluric effects in NGC 7027 have negated this choice.

In order to correct our average for this problem, we have weighted all lines by a factor $[1 - c(\mathrm{C/R})_2/(\mathrm{C/R})_1]^2$. This factor goes to zero when the denominator in equation (17) is zero, and approaches 1 for lines which are strongly collisionally enhanced.

Column (6) shows that even for lines not affected by the above, the accompanying errors can be appreciable. Although these uncertainties result from each step in the procedure as described above, we shall focus here on the two main sources of error.

First, as is evident from column (3), the uncertainties in the theoretical C/R values are significant. As discussed previously and as can be seen from comparing Tables 3 and 4, these errors can be reduced by including only high density ($n_e \geq 2 \times 10^4$) objects in the analysis. However, the exponential dependence of the C/R factors on T_e can still cause appreciable errors. This is clearly seen in Figure 2 of PTP1, which shows the behavior of 1 + C/R as a function of temperature for several lines.

Second, although we "observe" the quantity 1 + C/R, it is the value C/R that is needed to determine γ. This can result in a significant increase in the relative error for lines with small to moderate collisional enhancement. To demonstrate this more clearly, let us assume for simplicity that we have a fictitious reference line with zero collisional enhancement. Equation (16) then becomes

$$\mathrm{const} = 1 + \gamma(C/R)_1 . \tag{18}$$

If a line whose collisional enhancement we wish to measure has C/R = 0.5, the percentage error in the constant will increase by a factor of 1.5/0.5 = 3 when the 1 is subtracted. Thus, even an observational uncertainty as low as 10% will be increased to 30% in this step. Mathematically, the problem results from trying to measure C/R from the quantity 1 + C/R, where often $\mathrm{C/R} \ll 1$. Physically, this translates into the common sense result that the smaller the collisional effect, the more uncertain its measurement. This can be seen in our data by comparing the entries in column (6) between Tables 3 and 4. The percentage errors are much greater in NGC 7026 due to the relative weakness of collisional effects in this object. This was expected from the onset; we have included this object solely to demonstrate the uncertainties acquired in the determination of γ.

Similarly, we can see that our other method for determining γ, by self-absorption, also results in appreciable errors. This is largely due to the observational errors in the line ratios used.

The problems discussed above make it difficult to substantially decrease the uncertainties obtained in this study, but we make some suggestions below. First, it is essential to observe only high-density objects, but even these will result in appreciable uncertainties due to the strong temperature dependence of the collisional effects. Second, the preceding discussion makes it obvious that only strongly collisionally enhanced lines should be considered, and that these lines should be observed with respect to a line showing very small enhancement. Unfortunately, the lines most affected by collisions suffer from a host of other problems. The line that is the most enhanced by collisions, λ10830, can be substantially affected by dust and telluric absorption, and is also somewhat of an observational challenge. Both λ7065 and λ3889 suffer from uncertainties in self-absorption, with λ3889 having the additional problem of blending with H8, and λ7065 subject to possible telluric absorption. The singlet line λ7281 also has nonnegligible self-absorption and telluric effects. In addition, unlike λ6678, there is a significant difference between the case A and case B recombination intensity. Our data suggest that γ is most accurately determined from λ7065, but any observations of this line should be carefully planned to avoid telluric contamination. We note here that our best average for NGC 7027 is slightly weighted toward λ7065, which has an uncertain telluric correction. This uncertainty will affect the derived γ. If we had made no correction for telluric absorption, for example, our best average would drop to 0.83 ± 0.55.

Finally, we wish to remark on the discrepancy between our results and those of PTP2. As mentioned previously, PTP2 used the line ratios λ10830/λ5876 and λ7065/λ5876 to derive γ from a consideration of self-absorption. The 10830 line suffers from telluric absorption, dust destruction, and observational uncertainties. These uncertainties are further exacerbated by the more recent observations of Rudy et al. (1992), who found λ10830 to be *stronger* than expected in NGC 7027. Obviously, the observational situation must be clarified. In addition, the *recombination* intensity for λ7065 was underestimated by Brocklehurst (1972). The new data from Smits (1994) are roughly a factor of 1.4 higher. Thus, previous determinations of the collisional enhancement of this line have been *overestimated* by the same factor. This would cause the derived γ for this line to be only 70% of its actual value.

In summary, our best average γ for NGC 7027 implies that there is no depopulation of the $2\,^3S$ state, although the appreciable errors make this result somewhat uncertain. However, we argue that any attempts to observationally determine γ will suffer from similar uncertainties. We therefore feel that there is no compelling observational evidence for any depopulation of the $2\,^1S$ level. This is supported by the failure to discover any such mechanisms theoretically. Thus, we suggest that measured He I line intensities should be corrected for collisions by using the formulae in this paper with $\gamma = 1$.

The authors wish to thank several people for providing important atomic data used in this paper: P. M. J. Sawey and K. A. Berrington, for providing the He I collision strengths, prior to publication, and S. Nahar and A. Pradhan for providing data from the Opacity Project. We also thank R. R. Robbins for kindly sending his manuscript on self-absorption in the He I singlets. Finally, we acknowledge useful discussions with M. Peimbert. This work was partially supported under grants from NSF (AST 93-19034) and NASA (NAGW-3315).

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