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THE SPECTRUM OF NGC 7027

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ABSTRACT

NGC 7027 is the brightest planetary nebula (PN) in the sky despite the fact that it is dimmed by 14 db (i.e., about 3.5 magnitudes) of local and interstellar extinction. It is also one of the intrinsically most dense and luminous of PN, although it may have evolved from a progenitor in the 1.5–5 $\mathfrak{M}_\odot$ range. Observations secured with the Hamilton echelle spectrograph at Lick Observatory and with the IUE are analyzed to obtain nebular plasma diagnostics and chemical abundances. Much of the nebular plasma seems to have a density $N_e \sim 60{,}000$ cm^{-3} and temperature $T_e \sim 14{,}000$ K, although the [Ne IV] and [Ar IV] auroral/nebular line ratios suggest a $N_e \sim 54{,}000$ cm^{-3} and $T_e \gtrsim 16{,}000$ K zone, while [S II] suggests a zone at $N_e \lesssim 30{,}000$ cm^{-3}, $T_e \sim 13{,}000$ K. Nebular models based on currently available theoretical stellar fluxes for hot stars ($T \sim 180{,}000$ K to 200,000 K) predict He II λ4686 too strong and [Ne V] too weak. It is suggested that the stellar radiation field is greatly enhanced shortward of 130 Å because of a dense non-LTE wind. The chemical composition appears to be that of a "normal" carbon-rich object rather than that of a nitrogen-rich object such as NGC 2440, which presumably had a massive progenitor.

Key words: planetary nebulae–spectroscopy

1. Introduction

NGC 7027 is probably the best-studied planetary nebula (PN) in the sky for a number of very good reasons.

1. It is one of the few PN for which an accurate distance estimate is available (see, e.g., Masson 1989).
2. It is intrinsically one of the most luminous PN; in fact, it appears to lie at the upper limit of luminosity as determined by Ciardullo *et al.* (1989) from their studies of PN in distant galaxies.
3. It is one of the densest of PN and its inner, expanding, H II shell is surrounded by an extensive, dusty, molecular cloud. The internal dust hides much of this PN.
4. The PN nucleus (PNN) is the core of a progenitor that was probably not near the upper mass limit (5 to 8 $\mathfrak{M}_\odot$) of stars that can produce PN, although the total mass of the ejected material may have exceeded 0.5 $\mathfrak{M}_\odot$. It may be evolving rapidly, declining in luminosity since the PN was formed, the order of 1000 years ago.
5. NGC 7027 has a high optical surface brightness (in spite of $\sim$ 3.5 magnitude attenuation by dust) and an extraordinarily rich spectrum in the ultraviolet, optical, and infrared regions. It has been a favorite object for spectroscopists for many years.

These features make NGC 7027 an especially engaging object for an examination of a late stage in the life of a star. What can the chemical composition of the envelope tell us about events in late stages of stellar evolution? What can the core tell us about evolution to the white-dwarf stage? To answer these questions properly, we need to have a reasonably accurate distance estimate.

The distance determination problem seems to have been solved in a satisfactory manner by Masson (1989) who obtained VLA maps with a resolution of 0."35. By careful comparison of isophotic maps secured over a baseline of even a few years, the angular rate of expansion can be found and compared with the radial expansion rate of the H II region. One must allow not only for the bulk motion of the gas but also for the movement of the ionization front into the molecular cloud, a problem Masson solved with an appropriate model, whereby he was able to obtain a distance of 880 ± 150 pcs. The limit on accuracy is imposed by limitations of the model and the assumption that NGC 7027 is strictly an ellipsoidal shell.

Pottasch *et al.* (1982) had determined the distance of NGC 7027 by assuming its luminosity to be the maximum allowed a PN. Using then-available data they estimated the distance of NGC 7027 as between 1000 and 1300 pcs. A more precise estimate can now be made using data by

Ciardullo *et al.* (1989). They find the upper limit of luminosity of a PN to correspond to a monochromatic absolute magnitude, $M(5007) = -4.48$, while $m(5007)$ is related to the 5007 flux by $m(5007) = -2.5 \log F(5007) - 13.74$. Using $\log F(\mathrm{H}\beta) = -10.12$ (Shaw and Kaler 1982), assuming the extinction constant $C(\mathrm{H}\beta) = -1.37$, and adopting $I(5007)/I(\mathrm{H}\beta) = 14.0$ (Kaler *et al.* 1976), we obtain $\log F(5007) = -7.60$ (corrected for interstellar extinction), whence we find a distance of 890 pcs. The agreement with the Masson result is fortuitous but does support the suggestion of Pottasch *et al.* (1982) that the glowing shell of NGC 7027 may be one of the most luminous possible planetary nebulae.

The spectrum of NGC 7027 has been extensively studied (see, e.g., Kaler *et al.* (1976) and references to earlier work therein). Special features of the spectrum have been studied by Péquignot, Baluteau, and Gruenwald (1988) and Péquignot and Baluteau (1988). Extensive studies of the infrared have been carried out by many workers (e.g., Condal *et al.* 1981; Treffers *et al.* 1976; Russell, Soifer, and Willner 1977; Bregman *et al.* 1983).

Interpretations of spectroscopic data to estimate chemical composition require some kind of a model for the H II zone. Because of heavy, irregular extinction by dust, optical-region data are of limited usefulness, unless combined with IR and radio-frequency measurements. Early 10-μm measurements by Becklin, Neugebauer, and Wynn-Williams (1973) and pioneer radio-frequency isophotes by Scott (1973) and by Balick, Bignell, and Terzian (1973) showed that NGC 7027 was not an irregular amorphous object as had been previously supposed but was a rather orderly symmetrical shell involved in a cloud of obscuring dust. Atherton *et al.* (1979) combined their monochromatic electronographic data for Hβ, He II, and various strong forbidden lines with radio-frequency data to derive a hollow prolate spheroidal shell tilted about 30° to the line of sight. These and more recent data by Basart and Daub (1987) and by Masson (1989) suggest a somewhat deformed shell with outer dimensions about 12″.4 × 6″.8 and internal major and minor axes of 11″.0 and 5″.6. The hollow core of the shell apparently has been scoured out by a brisk stellar wind. The outer edge of the H II region is expanding at a rate of 21.5 km sec^{-1} (Sabbadin 1984), while the surrounding molecular cloud expands at a rate of 17 km sec^{-1} (Sopka *et al.* 1989). Thus, the net rate of expansion of the H II region into the molecular cloud is about 4.5 km sec^{-1}.

The mass of the H II shell appears to be of the order of 0.01 to 0.02 $\mathfrak{M}_\odot$, while that of the residual stellar core is probably about 0.6 to 0.8 $\mathfrak{M}_\odot$. With an adopted distance of 880 pcs, annual mass-loss rates in solar units of 4.1×10^{-5} (Jura 1984), 7.7×10^{-5} (Knapp and Morris 1985), and 9.3×10^{-5} (Sopka *et al.* 1989) have been found. Assuming a constant expansion velocity of 17 km sec^{-1}, the approximately 30″ radius of the molecular cloud implies an age for the ejected red-giant shell of about 7500 years, an age much greater than that of the PN itself. The corresponding masses are 0.36, 0.68, and 0.82 $\mathfrak{M}_\odot$. Reay (1983) studied an outlying halo in Hβ radiation that is about 100 times fainter than the bright image but with dimensions of about 55″ × 47″. Presumably, it is caused by light scattered by dust particles.

Few molecular species are found in NGC 7027 compared with the variety found in galactic molecular clouds. The most prominent is CO (Mufson, Lyon, and Marionni 1975; Knapp *et al.* 1982; Masson *et al.* 1985; Thronson and Bally 1986). The latter searched for a large number of other molecules and found only CN, possibly originating from the dissociation of HCN. This molecule was later found by Sopka *et al.* (1989). Molecular hydrogen occurs at the edge of the H II zone. It appears to be excited partly thermally (possibly by shocks as the more rapidly moving ionized gas collides with the outer, slowly moving layers) and partly by fluorescence from the strong UV radiation field of NGC 7027 (Tanaka *et al.* 1989).

The overwhelming bulk of the energy emitted by NGC 7027 is in the form of thermal emission by dust. In η Carinae an even larger fraction of the radiation from the central source is being degraded to IR radiation.

Extensive studies of the infrared radiation of NGC 7027 have been carried out (Telesco and Harper 1977; McCarthy, Forrest, and Houck 1978; Melnick *et al.* 1981; Gee *et al.* 1984); see also Barlow (1983) and Roche (1989) and references therein cited. The IR continuum arises primarily from thermal emission by dust. This material is not at a uniform temperature. Inner strata that contribute about 25% of the IR energy output are hotter than 100 K. A surrounding cooler zone whose temperature is about 90 K emits 68% of the total IR flux and absorbs much of the nebular radiation such as Lyman-α. Measurements by Gee *et al.* (1984) at 370 μm suggested an outer cloud with a temperature of about 20 K.

Infrared lines probably contribute about 3% of the total emission in this spectral region. The emission features at 8.6 μm and 11.3 μm arise in a shell around the H II region and that defined by the 10-μm continuum which is emitted by hot dust. The grains that emit these lines may be destroyed in the H II region where they are subjected to quanta of energies exceeding 36 eV (Smith, Larson, and Fink 1981).

Mass-loss rates for AGB stars in advanced evolutionary stages are determinable often by measuring CO line profiles, whose half-widths give the expansion velocity, while the fluxes give the mass-loss rates in CO. To obtain the total mass-loss rate one must know $N(\mathrm{H_2})/N(\mathrm{CO})$. Knapp gives a mass-loss rate of 0.00011 $\mathfrak{M}_\odot$ per year. Other estimates, based on molecules existing in the outer envelope, have suggested rates from 0.00001 to 0.00044. Zuckerman (1978) noted that the ratio of the CO luminosity of NGC 7027 to its IR luminosity was ten times larger than for other evolved stars with large mass-loss rates, and he suggested that the luminosity of the central star had faded by a factor of 10 since it ejected the molecular shell about 1000 years ago. A similar conclusion was reached by Jura (1984).

Masson (1989) derived a simple expansion age of 600 years. Jura (1984) has found an upper limit to the transition time from the red-giant stage to the PN phase by locating the ionizing front nearest the PNN. With $r = 3''.5$, $V = 17$ km sec^{-1} for the molecular envelope, a value of 1000 years is found. Using evolutionary arguments Pottasch (1983) suggested that the PNN may be on the horizontal branch of its track near the point where a rapid decline in luminosity and temperature should begin. According to these predictions, the luminosity of the star should fall by a factor of 10 in the next 1000 years. Other evolutionary arguments (e.g., Wood and Faulkner 1986) yield 2000 to 3000 years. As we shall see the abundance pattern for NGC 7027 favors a progenitor mass in the range of 1.5 to perhaps as much as 4 or 5 $\mathfrak{M}_{\odot}$. Additional evidence for an original star in this mass range is suggested by the unremarkable CO velocity of 17 km sec^{-1} (Zuckerman 1989). A massive object would have a much higher CO shell velocity (Table 1).

2. Observational and Reduction Procedures

The immediate objective of our program is to compare the predicted emissivity of the bright H II ring of NGC 7027, as based on a simple spherically symmetrical model with high-dispersion spectroscopic data.

The availability of the Hamilton echelle spectrograph makes it possible to secure high-dispersion spectra from about 3600 Å to 11000 Å and to measure lines over a large range in intensity. In an echelle spectrograph the observed spectrum is spread out in very high orders which are separated from one another into nearly parallel strips with the aid of a cross-dispersing prism, i.e., an arrangement in which the prismatic dispersion is perpendicular to the grating dispersion. Wavelengths between 3600 Å and 11000 Å are concentrated in orders from 150 to 50, with each order containing only a limited spectral range.

We note that we do not usually observe the integrated flux of the PN or its bright ring but rather an integration along a narrow pencil of area dA, through some part of the nebular image. Theoretical predictions customarily give the integrated monochromatic fluxes of the PN. In practice, we usually observe such integrated fluxes for only strong lines, often with narrow bandpass filters or by photoelectric photometry, while for the weaker fluxes one must use a slit spectrograph that gives the nebular flux only along a narrow strip passing through some portion of the nebular image. One of the longer-range objectives of our investigations ultimately will be to modify the modeling program so that we can take narrow pencils through a portion of the theoretical projected image to compare with the observations. For example, we can select a pencil through the bright ring of a double-ringed object such as NGC 7662 or NGC 7009. In this paper we assume that the $4'' \times 2''$ pencil actually used gives a fair sample of the bright ring in NGC 7027. Note, however, that in addition to substantial interstellar extinction, NGC 7027 suffers from extensive internal dust absorption. The brightest part of NGC 7027 corresponds to the least-obscured region in the bright ring of the nebula.

3. Some Comments on the Data Reduction

Assessment of the echelle data is involved and quite lengthy. We have utilized the Kitt Peak IRAF[1] echelle package to reduce and analyze our data.

Since the area of the 800 × 800 CCD chip is smaller than that over which the spectrum is spread, six physical positionings of the CCD chip in the echelle image format are required to cover the spectral region from 3550 Å to 9000 Å. The measurements and observations we must secure for each of these six positions are as follows.

1. "Flat field" of laboratory continuum source. These "exposures" are obtained with a longer slit (6″) than those used for stellar or nebular exposures. The nebular and standard comparison star exposures are divided by these "flat-field" exposures on a pixel-by-pixel basis to allow for small-scale variations in the response of the CCD chip.
2. Thorium-argon comparison arc exposures are taken to establish the wavelength scale for each echelle order.
3. Standard comparison stars of accurately known energy distribution are preferably selected from objects such as BD +28°4211, whose spectra are weakly perturbed by H lines. Occasionally, we must use late B-type or A stars such as 58 Aquilae and carefully interpolate over the Hα, Hβ, and Hγ lines.
4. Finally, since the nebular lines show a huge intensity range, we must take a graded series of exposures, typically from one minute to 90 minutes. To measure the weakest lines, somewhat longer total dwell times are often needed. We can add exposures taken even on different nights and allow for slight wavelength displacements.

A severe problem is posed by the great intensity range, over a factor of 300,000, between the strongest lines and weakest features of the spectrum. Thus, if we expose for the weakest lines, the strongest lines will be so badly overexposed or saturated that charges will drain from the pixels, both along the dispersion and perpendicular thereto. This "bleeding" from a saturated region often requires that we place the chip in such a position that the strong line falls out of the field. This subterfuge is not available for lines in the immediate proximity of the strong [O III], [N II], or Hα emissions, but sometimes one

[1]IRAF is distributed by National Optical Astronomy Obsrvatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.

TABLE 1

Some Basic Data for NGC 7027

Position	α = 21 hr 05 m 09.5s (1950) δ = +42 03' 03" (1950) (Harris and Scott 1976)
log F(Hβ)	= −10.12 ± 0.01 (Shaw and Kaler 1982)
Radio fluxes:	1.465 GHz 1.48 ± 0.03 Jy (Baars *et al.* 1977) 4.885 5.66 ± 0.01 1°4.965 6.1 ± 0.125
Extinction:	A(V) = 3 ± 0.3 (Atherton *et al.* 1979) A(V) = 3.1 or C(Hβ) = 1.43 (1979), C(Hβ) = 1.37 (Shaw and Kaler 1982; Kaler *et al.* 1976)
Distance:	880 pc ± 150 (Masson 1989)
Mass of envelope:	< 5 m(sun) (Knapp *et al.* 1982)
Rate of mass loss:	dm/dt = 0.07 − 1.1 × 10^{-3} (various workers)
Structure:	ellipsoidal shell or outer dimension, 12.4" × 6.8" thickness = 0.6" (see text)
Velocity of expansion:	H II shell ~ 21.5 km/sec (Sabbadin 1984) C O shell ~ 17 km/sec (Sopka *et al.* 1989)
Dust Shell:	Dimensions: 47" × 55" (Reay 1983) Temperature: 20°K < T < 230°K (most is at 90°K) Optical depth: ~ 0.1 at 1549 Å (Harrington 1989)
Most of the emission of NGC 7027 is from heated dust molecular cloud:	CO, H_2, CN
Age of nebula:	600 years (simple expansion, Masson 1989) 1000 years (Pottasch 1983; Jura 1984) 2000–3000 years (evolution of central star, Wood & Faulkner 1986)
Central star:	m = 16.32 (Jacoby 1988) L = 4900 $L_\odot$, T_{eff} = 180,000°K, R = 0.072 $R_\odot$ E(B−V) = 0.85 Mass = 0.65 − 0.7 $m_\odot$ (Wood & Faulkner 1986) Mass (progenitor) = 1.5 − 5 $m_\odot$

can allow for the effects of the "bleeding" when it extends over several orders.

Among other sources of annoyance are some defects in the chip, which cannot be removed by the flat-field procedure and which produce small depressions on the spectrum. If a line is broad we can smooth over such dips; otherwise, we have to reposition the chip in the echelle spectral format.

There are the usual sources of uncertainty arising from errors in the adopted stellar energy distribution and in the atmosphere extinction. Since many of the observations are secured on nights with some moonlight, an absolutely clear sky is required, except possibly for some of the strongest lines where we still can make reliable measurements of ratios of closely blended lines such as λ3970 H I and λ3969 [Ne III].

Furthermore, the guiding may not be exactly the same from one exposure to the next. We evaluated this effect by comparing lines common to more than one chip position. The errors from this cause were of the order of 3% to 5% and random in character.

By comparing intensities of the same line as measured in different nights and with different chip settings, we concluded that for optical region lines weaker than 0.05 on the scale $I(\mathrm{H}\beta) = 100$, the random error will be of the order of 30% to 60%. For $0.05 < I < 0.10$ typical errors are 25% to 40%, for $0.10 < I < 0.3$ the mean error range appears to be 15% to 30%, and for $0.03 < I < 1.0$ errors of 10% to 20% are expected. Anticipated errors in the range $1 < I < 10$ are 7% to 12%, while for stronger lines we estimate the error to be of the order of 5% to 7%. Toward the edges of each order the errors tend to be larger and, of course, lines affected by bleeding from overexposed strong lines in neighboring orders are less accurate than nearby lines that are not so impacted. Table 2 lists the dates, dwell times, and echelle image format position-index of our observations of NGC 7027. Image format position-index 1 references the approximate spectral range λλ3600–4300, position-indices 2 and 3 are required to cover λλ4300–5900, and position-indices 4, 5, and 6 are required to cover λλ5900–11000.

We have yet to assess the infrared extreme of the Hamilton echelle spectra, 8700 Å to 11000 Å. The problem here is that there are no suitable comparison lines with which to determine the wavelength scale and one has to "bootstrap up" from known nebular lines.

TABLE 2

Optical Region Observations

Date	Position	Dwell Times (min.)
Jun 28 1986	(1)	5, 20, 60
	(2)	20
	(3)	40[a]
Jun 29 1986	(2)	5, 0.133
	(3)	5, 25
	(4)	5, 25
	(5)	0.33, 5, 25 (Hα region)
	(6)	5, 25
Aug 04 1987	(1)	5, 40
Aug 05 1987	(1)	90
	(3)	40
Sep 03 1987	(2)	26[a]
	(3)	20[a]
	(4)	16[a]
	(5)	10[a]
Sep 04 1987	(5)	60
	(6)	5, 75
	(4)	80

[a] Some interference from clouds; comparison stars were BD+28°4211, 58 Aquilae.

4. The Ultraviolet Region of the Spectrum of NGC 7027

Many workers have observed the spectrum of NGC 7027 with the IUE with exposures ranging from 12 minutes to 420 minutes (see Perinotto, Panagia, and Benevenuti 1980). Table 3 lists the IUE observations of NGC 7027. First, we used the four spectra of NGC 7027 that are shown in the atlas of planetary nebula spectra (Feibelman *et al.* 1988). The long SWP exposure was used for the weaker lines and the short SWP measurement for the strong lines that were saturated on the long exposure. In the LWR range only the short exposure was used, since all the lines except for 2470 Å and 3204 Å are saturated on the 180-minute exposure. The Mg II doublet shows some structure, although the stronger component is again overexposed as is the [Mg V] line at λ2783.

TABLE 3

IUE Observations of NGC 7027

Date	Image No.	Dwell Time (min.)
Jun 17 1982	SWP 17240	45
	SWP 17242	12
Mar 29 1983	SWP 19579	420
	SWP 19877	180
Jan 25 1979	LWR 5615	35
	LWR 15105	300
May 03 1983	LWR 15861	180
	LWR 15862	27

Note that in the SWP range there is a fairly strong continuum which amounts to about 1.1×10^{-13} ergs cm^{-2} s^{-1} Å^{-1}. This is just about the flux one would predict from the Hβ, taking into account the contributions of H, He, He^{+}, and the two photon continua for $T_e \sim 15{,}000$ K and $N_e \sim 60{,}000$ cm^{-3}. There is no evidence for any stellar contribution. The 420-minute exposure was obtained by Fred Bruhweiler, who was looking for interstellar absorption lines. This observation, SWP 19578, points out an interesting aspect of long IUE high-dispersion exposures on planetary nebulae. It yielded very little information, as all the strong lines were saturated while the weak lines were not sufficiently exposed to give good fluxes.

5. Line Intensities, Extinction Correction, and Diagnostics

Table 4 lists the measured IUE intensities. Successive columns give the wavelengths in Å, the responsible ions, the adopted observed flux, the interstellar extinction coefficient parameter $f(\lambda)$ taken from the work of Seaton (1979), and the flux corrected for interstellar extinction. The last column gives the corrected intensity based on the scale $I(\mathrm{H}\beta) = 100$.

Table 5 gives the optical region spectrum 3670 Å to 8750 Å, H23 → Pa12. The table supersedes a preliminary version (Aller and Keyes 1988) which covered a more-limited wavelength range. It involves also a superior reduction method and much more extensive observational data. Successive columns give the wavelengths in Å, the species responsible, and the observed relative flux (on the scale Hβ = 100) not corrected for interstellar extinction.

In the optical region and the UV we have observed lines of H, He I, He II, C II, C III, C IV, [N I], N II, [N II], N III, N IV, N V, O I, [O I], O II, [O II], O III, [O III], O IV, [F IV], [Ne III], [Ne IV], Mg I, [Mg I], Mg II, [Mg V], Si II, Si III, Si IV, [P II], [S I], [S II], [S III], [Cℓ II], [Cℓ III], [Cℓ IV], [Ar III], [Ar IV], [Ar V], [K IV], [K V], [K VI], [Ca V], [Mn V], [Fe III], [Fe V], [Fe VI], and [Fe VII].

The 3100 Å to 3600 Å spectral region cannot be studied with the Hamilton echelle spectrograph. We have utilized measurements of [Na IV] and [Ne V] secured as a by-product of a study of the Bowen fluorescent mechanism by Likkel and Aller (1986). These data are in reasonably good accord with the results of Kaler *et al.* (1976). For other features in this region we have relied mostly on data by Kaler *et al.* (1976).

To correct optical fluxes for interstellar extinction, we use $C = 1.37$ (Kaler *et al.* 1976; Shaw and Kaler 1982). A comparison of the He II λ4686 and λ1640 fluxes with theoretical predictions for $T_e = 14{,}000°$, $N_e = 60{,}000\ \mathrm{cm}^{-3}$ suggests $C = 1.47$ as the appropriate value, which we employ for comparing IUE data with the optical region. The disparity with the optical value of 1.37 could be attributed to a possible scaling error in the flux calibrations or accidental errors in measurements of line fluxes. If we use $C = 1.37$ throughout, the conclusions of this paper are not affected.

Our optical data differ from much previous work in that (a) we can observe relatively faint lines, and (b) the measurements apply to a very limited region of the nebula. We chose the brightest part of the image which is actually a small, relatively unobscured section of the bright ring. The physical mechanisms for excitation include: (a) direct recombination for lines of H I and He II, (b) both direct and dielectronic recombinations for many faint ionic lines of C, N, O, Ne, etc., (c) collisional excitation of metastable and low-lying levels, and (d) the Bowen fluorescent lines.

The main objective of this investigation is to improve our knowledge of the plasma diagnostics, $\langle N_e \rangle$, $\langle T_e \rangle$, and fluctuations thereof, as well as the chemical composition of the bright ring, not only for the abundant elements that have been extensively studied but also for elements such as Ca and K. We try to assess how much material is involved in grains. Finally, we seek to gain some idea of the accuracy of the physical parameters, many of which have been improved in recent years, e.g., the collisional strengths for ions in the second row of the periodic table such as Cℓ III, Cℓ IV, Ar III, Ar IV, and Ar V, and charge exchange cross sections.

Looking ahead further, we urgently need a comprehensive recombination theory so that the extensive set of weak permitted lines of C II, O II, and N II that are so prominent, particularly in NGC 7009 and NGC 6778, can be properly interpreted. Why are they not more conspicuous in NGC 7027, since recombination rates are so strongly favored by higher densities there? Perhaps they are excited largely by a stellar radiation field in NGC 7009 and NGC 6778. We have used recent electronic collision strengths for [Cℓ III] (Butler and Zeippen 1989) and [Ar IV] (Zeippen, Butler, and Le Bourlot 1987), whereas for most other ions we have relied on the compilation by Mendoza (1983).

A number of diagnostic line ratios are present. The [N I] λλ5200/5198 ratio, 0.59 ± 0.05, lies near the high-density limit of 0.54. Comparison of the [O III] λλ4363/[4959+5007], [O II] auroral/nebular, λλ7319+7330/3727 C III λλ1907/1909, Si III λλ1884/1892 ratios suggests $T_e \sim 14{,}000$ K, $N_e \sim 62{,}000\ \mathrm{cm}^{-3}$, for these ions. A somewhat higher density, $\sim 80{,}000\ \mathrm{cm}^{-3}$, is suggested by [Cℓ III], λλ5517/5537 and λλ5517/3342 ratios. For [Ne IV] the high-excitation lines, λ2423, λ2425, and the auroral/nebular line ratios, as well as [Ar IV] λλ4711/4740, indicate $T_e \sim 16{,}000$, $N_e \sim 56{,}000\ \mathrm{cm}^{-3}$. [N II] λλ5755/[6548+6584] at $T_e = 14{,}000$ K would suggest $N_e \sim 35{,}000\ \mathrm{cm}^{-3}$, values consistent with the [S III] data. The [S II] nebular and auroral-type transitions indicate $N_e \sim 30{,}000\ \mathrm{cm}^{-3}$. Shaw and Kaler (1982) found $T_e = 15{,}000$ K from the continuum.

These diagnostics indicate that the bulk of the optical radiation arises from rather dense regions with an electron temperature near 14,000 K and an electron density of the order of 60,000 to 80,000 electrons cm^{-3} with some indication that ions of N^+ and S^{++} may be concentrated in regions of $N_e \sim 35{,}000\ \mathrm{cm}^{-3}$. The lines of higher excitation, [Ar V], [Ne IV], and [Ne V], indicate strata of $T_e \sim 16{,}000$ K. Péquignot and Baluteau (1988) derived densi-

TABLE 4

Derived IUE Intensities

Wavelength	Ion	Adopted Flux × 10^{12}	f(λ)	Derived flux × 10^{12}	Intensity I(Hβ) = 100
1238.3 Å	N V	0.12	1.641	31	41.0
1334.2	C II	0.10	1.418	12.2	16
1400.6	O IV,Si IV	0.61	1.308	51.1	67.5
1485.0	N IV]	0.70	1.231	45	60
1548.3	C IV	13.1	1.185	723	956
1550.86	C IV	7.7		425	562
1575.7	[Ne V]?	0.21:	1.169	11.0	14.6
1601.3	[Ne III]	0.28	1.157	14.0	18.5
1640.2	He II	5.0	1.138	235	312
1666.0	O III]	0.70	1.13	32.1	42.5
1749.5	N III]	0.62	1.121	28	36.5
1817.25	Si II	0.05:	1.143	2.4:	3:
1884.0	Si III]	0.22	1.200	12.8	16.9
1892.0	Si III]	0.17	1.208	10.1	13.4
1906.71	C III]	4.23	1.225	267	354
1908.78	C III]	6.85	1.225	433	573
2325.5	C II	0.61:	1.353	60	79
2327.0	C II,O III	0.48:		47	62
2421.4	[Ne IV]	1.32	1.122	59	78
2424.5	[Ne IV]	0.43		19	25.4
2470.4	O II	0.70	1.027	23	30
2511.0	He II	0.31	0.957	7.9	10.5:
2732.2	He II	0.61	0.701	6.5	8.6:
2782.3	[Mg V]	0.83	0.660	7.8	10.3
2796.0	Mg II	0.93	0.647	8.3	11.0
2800.1	Mg II	1.05		9.4	12.4
2828.8	He I	0.125	0.625	1.0	1.4
2835.2	O III	0.88		6.9	9.2
2852.6	Mg I	0.25	0.610	2.0	2.6
2927.2	[Mg V]	0.48	0.560	3.2	4.2
2933.3	Mg II	0.12		0.81	1.1
3047	O III	1.5	0.496	8.0	10.6
3133.2	O III	10.5	0.455	4.7	65
3203	He II	3.6	0.426	15.2	20

[a] F(4686)/F(4861) = 0.426, F(4861) = 7.59 × 10^{-11}, C = 1.47+0.07

: = uncertainty of more than 20%

TABLE 5

Spectrum of NGC 7027

3670 to 8750 Å

Wavelength Å	Identification	I_{OBS}	Wavelength Å	Identification	I_{OBS}
3673.7	H 23	0.243	3839.5	[Fe V]	0.059
3676.4	H 22	0.28	3843.0	O II	0.22
3679.3	H 21	0.32	3853.6	Si II	0.035
3682.8	H 20	0.357	3856.0	Si II	0.053
3686.7	H 19	0.41	3858.1	He II	0.137
3689.7		0.06	3862.6	Si II	0.100
3691.6	H 18	0.45	3868.8	[Ne III]	57.1
3694.3	He II	0.033	3887.4	He II	0.151
3697.2	H 17	0.53	3889.0	H 8, He I	8.27
3698.5	He II	0.026	3891.3	[Fe V]	0.085
3702.4	He II	0.033	3895.5	[Fe V]	0.085
3703.8	H 16	0.64	3920.7	C II	0.048
3705.0	He I	0.17	3923.5	He II	0.169
3712.0	H 15	0.75	3926.4	He I	0.070
3715.1	He II, O III	0.08	3954.5	O II	0.055
3717.5		0.04	3956.7	O IV	0.057
3720.2	He II	0.026	3961.6	O III, [F IV]	0.025
3721.9	H 14, [S III]	2.06	3964.8	He I	0.249
3726.0	[O II]	7.88	3967.5	[Ne III]	20.5
3728.7	[O II]	2.88	3968.5	He II	0.24
3732.8	He II	0.039	3970.0	H 7	8.65
3734.3	H 13	1.11	3997.4	[F IV]	0.024
3736.8	O IV	0.19	4009.3	He I	0.056
3748.7	He II	0.045	4025.6	He I, He II	1.09
3750.1	H 12	1.38	4034.8	O II	0.022
3754.6	O III	0.416	4046.5	[Fe III]	0.030
3757.3	O III	0.114	4060.2	[F IV]	0.057
3759.8	O III	2.36	4068.7	[S II]	3.76
3768.9	He II	0.055	4070.3	C III	0.237
3770.6	H 11	1.74	4071.3	[Fe V]	0.056
3774.0	O III, [Fe IV]	0.10	4072.1	O II	0.061
3781.6	He II	0.076	4074.0	O III	0.045
3791.3	O III	0.15	4076.2	[S II]	1.21
3796.3	He II	0.097	4078.9	C II	0.03
3797.8	H 10	2.54	4080.1	O III	0.029
3813.5	He II	0.125	4084.5	O II	0.030
3819.6	He I	0.357	4087.0	O II	0.02
3829.7	Ne II, N II	0.054	4089.2	O II	0.051
3833.8	He II	0.095	4097.3	N III	1.14
3835.4	H 9	3.49	4100.0	He II	0.486

TABLE 5 (Continued)

Wavelength Å	Identification	I_{OBS}	Wavelength Å	Identification	I_{OBS}
4101.7	H δ	15.5	4517.0	C III	0.05
4103.3	N III	0.514	4518.0	N III	0.026
4119.1	O II	0.031	4523.6	N III	0.0423
4120.7	He I, O II	0.113	4534.5	N III	0.04
4123	[K V]	0.06	4541.4	He II	1.43
4128.8	[Fe III]	0.066	4562.5	[Mg I]	0.02
4143.6	He I	0.151	4570.9	Mg I	0.562
4156.3	C III	0.063	4590.8	O II	0.031
4163.3	[K V]	0.166	4596.1	O II	0.031
4168.9	He I	0.042	4603.1	N V	0.029
4180.9	[Fe V]	0.026	4606.6	[Fe III]	0.111
4186.8	C III	0.192	4619.9	N V	0.033
4189.8	O II	0.043	4625.4	[Ar V]	0.097
4195.6	N III	0.027	4632.1		0.177
4199.8	He II	0.613	4634.1	N III	1.37
4227.5	[Fe V]	0.101	4638.9		0.048
4229.2	[Fe V]	0.027	4640.9	N III	2.66
4261.9		0.03?	4642.0	N III	0.324
4267.2	C II	0.366	4647.4	C III	0.48
4275.5	O II	0.04	4649.1	O II	0.146
4325.9	C III	0.034	4650.3	C III	0.158
4338.9	He II	0.92	4651.5	C III	0.068
4340.8	H γ	33.5	4654.4	N II?	0.016
4349.5	O II	0.035	4657.7	[Fe III]	0.240
4363.2	[O III]	17.6	4658.4	C IV	0.546
4368.5	O I	0.026	4661.6	O II	0.038
4379.2	N III	0.079	4663.8	C III	0.025
4387.8	He I	0.247	4665.6	C IV, C III	0.036
4414.8	O II	0.029	4669.2	[P II]	0.043
4417.1	O II	0.030	4673.5	O II	0.029
4434.4		0.03	4676.1	O II	0.045
4437.6	He I	0.041	4678.2	N II?	0.029
4448.0		0.03	4685.7	He II	42.6
4452.8		0.03	4701.3	[Fe III]	0.032
4458.7		0.031	4711.4	[Ar IV]	2.51
4471.4	He I	2.50	4713.2	He I	0.59
4481.3	Mg II	0.01:	4714.3	[Ne IV]	0.867
4491.2	O II	0.018	4715.7	[Ne IV]	0.280
4510.9	N III, [K IV]	0.057	4724.3	[Ne IV]	1.008
4514.6	N III	0.05	4725.7	[Ne IV]	0.826

TABLE 5 (Continued)

Wavelength Å	Identification	I_{OBS}	Wavelength Å	Identification	I_{OBS}
4740.2	[Ar IV]	8.88	5517.7	[C III]	0.259
4859.3	He II	2.65	5537.8	[C III]	1.010
4861.3	Hβ	100.0	5577.4	[O I]	0.468[a]
4893.4	[Fe VII]	0.08	5592.2	O III	0.22
4922.0	He I	0.89*	5604	[K VI]	0.046
4931.0	[O III]	0.23	5639.0	[Fe VI]	0.173
4938.6	[Ca VII]	0.125	5650.0		0.02
4944.6	[Fe VII]	0.060	5660.2		0.03
4948.6		0.200	5666.6	N II	0.036
4959.3	[O III]	512*	5677.0	[Fe VI]	0.191
4972.1	[Fe VI]	0.261	5679.7	N II	0.037
4988.8	[Fe VII]	0.114	5696	C III	0.033
4996.4		0.58	5721.1	[Fe VII]	0.517
5006.9	[O III]	1553*	5754.6	[N II]	9.93
5015.7	He I	1.50	5765.6		0.021
5028.2		0.113	5769.5		0.043
5029.6		0.080	5771.4		0.03
5041.3	Si II	0.293	5772.6		0.025
5047.9	He I	0.137	5776.4	[Mn V]	0.058
5056.5	Si II	0.200	5780.5		0.027
5131.2		0.181	5786.6	He II	0.035
5145.8	[Fe VI]	0.258	5790.8	He II	0.054
5151	[Fe III]	0.027	5794.8	He II	0.059
5158.9	[Fe VII]	0.187	5801.5	C IV	0.727
5176.4	[Fe VI]	0.226	5806.3	He II	0.061
5191.8	[Ar III]	0.337	5812.2	C IV	0.395
5198.0	[N I]	0.342	5815.9		0.08
5204.0	[N I]	0.201	5820.1	He II, [Ni IV]	0.078
5260		0.052	5828.6	He II	0.056
5270.3	[Fe III]	0.108	5836.5	He II	0.064
5277.8	[Fe VI]	0.073	5847.1	He II	0.068
5309.2	[Ca V]	0.408	5858.3	He II	0.068
5323.3	[Cℓ IV]	0.129	5863	[Mn V]	0.075
5335.3	[Fe VI]	0.175	5867.8	He II + ?	0.483
5346.0		0.25	5875.6	He I	20.7
5411.5	He II	6.32	5882.4	He II	0.081
5423.9	[Fe VI]	0.133	5885.9		0.092
5426.6	[Fe VI]	0.095	5891.0	[Mn V]	0.081
5470.9		0.108	5896.9	He II	0.095
5484.9	[Fe VI]	0.108	5913.5	He II	0.100

TABLE 5 (Continued)

Wavelength Å	Identification	I_{OBS}	Wavelength Å	Identification	I_{OBS}
5932.0	He II	0.111	6717	[S II]	4.7
5944.0		0.066	6731	[S II]	10.8
5953.1	He II	0.118	6850		0.12
5977.0	He II	0.128	6891	He II	1.53
6004.8	He II	0.146	7005	[Ar V]	12.2
6010.3		0.019	7054		0.06
6024.9		0.025	7059		0.06
6037.2	He II	0.180	7062		0.33
6074.3	He II	0.207	7065	He I	21.8
6083.8		0.037	7135	[Ar III]	73.2
6086.9	[Ca V], [Fe VII]	1.00	7171	[Ar IV]	1.90T
6101.8	[K IV]	1.001	7178	He II	1.75T
6118.3	He II	0.241	7237	[Ar IV], C II	2.58
6151.4		0.058	7263	[Ar IV]	1.68
6166.2	[Mn V]	0.050	7282		2.31
6170.7	He II	0.282	7320	[O II]	56
6210.2		0.019	7330	[O II]	45.8
6218.6	[Mn V]	0.029	7487		0.064
6221.0	[Mn V]	0.025	7493		0.056
6228.3	[K VI]	0.106	7500	He I	0.114
6233.8	He II	0.354	7530	[Cℓ IV]	2.13
6300.3	[O I]	25.1a	7535		0.126
6312	He II, [S III]	9.5	7593	He II	3.42
6347.5	Si II	0.147	7703		0.126
6363.8	[O I]	8.67a	7713		0.36
6371.3	Si II	0.281	7724		0.13
6393.6	[Mn V]	0.08	7726	[S I]	1.11
6406.5	He II	0.555	7736		0.18
6435.1	[Ar V]	4.0	7751	[Ar III]	23.4
6462.1		0.152	7816	He I	0.19
6518	[Mn VI]	0.12	7876	[P II]	0.47
6527		0.94	8046	[Cℓ IV]	5.70
6548	[N II]	92	8156	He I	0.088
6560	He II	22.3	8197		1.67
6563	Hα	760*	8237	He II	5.46
6578	C II	0.78	8250		0.21
6583	[N II]	267	8255		0.16
6601	[Fe VII]	0.15:	8258		0.19
6678	He I	8.35	8262	P 36	0.38
6684	He II	1.19	8265	P 35	0.41

TABLE 5 (Continued)

Wavelength Å	Identification	I_{OBS}	Wavelength Å	Identification	I_{OBS}
8269	P 34	0.37	8438	P 18	1.96
8273	P 33	0.27T	8447	O I	0.89
8277	P 32	0.29T	8463	He II	0.13
8281	P 31	0:39	8467.5	P 17	2.16
8287	P 30	0.51	8481	[Cl III]	0.37
8293	P 29	0.54	8500		0.45
8299	P 28	0.65	8502	P 16, [Cl III]	2.75
8307	P 27	0.67	8519	He II	0.12
8314	P 26	0.73	8546	P 15	3.07
8323	P 25	0.89	8579	[Cl II]	1.33
8334	P 24	0.92	8582	He I	0.20
8342		0.30	8594		0.17
8345	P 23	1.16	8598	P 14	3.74
8348		0.26	8617		0.39
8359	P 22	1.09	8626	He II	0.17
8362	He I, He II	0.31	8649	He I	0.19
8375	P 21	1.21	8667		0.30
8392	P 20	1.40	8665	P 13	4.6
8399	He II	0.116	8733		0.23
8414	P 19	1.50	8747		0.23
8422	He II	0.07	8750	P 12	5.4
8433	[Cl III]	0.44			

Table Legend:

: = Uncertainty estimated $\gtrsim$ 50%.

a = These [O I] lines are affected by contamination by atmospheric emission (air glow).

* = We adopt photoelectric measurements (see Kaler et al. 1976) of these line intensities.

T = Feature is affected by telluric line absorption (usually water vapor).

I_{OBS} = Line intensity not corrected for interstellar reddening.

ties of 80,000, 90,000, and 66,000 cm^{-3} and temperatures of 14,700 K, 12,500 K, and 16,500 K for H, He I, and He II, respectively.

Lines of [Fe VII] may prove to be useful diagnostics. Keenan and Norrington (1987) have calculated collision strengths for transitions arising in the d^2 levels of [Fe VII]. Unfortunately, λ6087 is blended with Ca V, thus limiting the usefulness of Figures 1 and 2 in their paper. Keenan (private communication) informs us that the λλ4989/5721 and λλ4844/5721 ratios indicate the [Fe VII] lines are formed in regions of high temperature (15,000 K to 20,000 K).

Table 6 gives ionic concentrations for each species. Successive columns in the table give the ion, the wavelengths of the lines involved, their intensities corrected for interstellar reddening, the selected electron temperatures and densities, $N(\text{ion})/N(\text{H}^+)$ as computed from appropriate equations of statistical equilibrium, and, finally, the adopted sums of all the observed ionic concentrations for each element in terms of $N(\text{H}^+)$ (see, e.g., Aller 1984; Osterbrock 1989).

Except for He the sum of the observable ionic concentrations does not give us $N(\text{element})/N/(\text{H}^+)$. For some elements such as Ca, only a small fraction of the total number of ions contributes to normally observable lines, in this instance [Ca V].

We use two methods to obtain nebular chemical compositions. One procedure is to calculate within the limitations of the basic assumptions the most precise model we can in order to represent the line intensities, certain aforementioned critical line ratios, and $\langle T_e \rangle$. That is, the first step is to devise a simple theoretical model that will give the best intensity representation practicable. The chemical composition used for this model provides a set of *model abundances*.

This model also gives for each element the fractional distribution of ions among possible ionization stages, $N(X_i)/N(\text{H}^+)$, so we can calculate $\Sigma N(X_i)/N$ where the summation is taken over observed ionization stages. Thus, for each element we can find the ionization factor

$$\text{ICF} = \sum \frac{N(X_i)}{\text{total}} \Big/ \sum \frac{N(X_i)}{\text{obs'd}} ,$$

by which the sum of the observed ionic concentrations from Table 6 is to be multipled to obtain $N(\text{element})/N(\text{H}^+)$. We call this procedure the *ICF method;* the result depends on the model chosen and the cut-off radius.

A prediction of a nebular spectrum with the aid of a theoretical model requires specification of a number of parameters: (1) geometry of the nebula: among the possibilities are a hollow shell, a double shell, and an equatorial belt with a polar cap of different density. We also specify the variation of density $N(r)$ as a function of r; (2) properties of the central star, radius (R^*), and energy $F_\nu(^*)$; (3) distance of the nebula, D.

The code contains the "hard" atomic data such as energy levels, ionization potentials, absorption coefficients, ordinary and dielectronic recombination coefficients, A-values, collision strengths, and charge exchange coefficients. It may also contain appropriate dust parameters. The program solves for the radiation field, derives the ionization equilibrium, calculates the local electron temperature from the energy balance condition, and then calculates the line emissivity per unit volume.

One stumbling block is the frequency dependence of the flux from the planetary nebula nucleus, PNN. Various F_ν(PNN) have been suggested by investigators, e.g., Hummer and Mihalas (1970), Husfeld *et al.* (1984), Köppen (1987), and Clegg and Middlemass (1987). Hummer and Mihalas treated the bound-free opacities of C, N, and O, in addition to those of H and He, but used an LTE approximation. Until very recently most investigations using the non-LTE approach have treated only H and He.

We have found that these models do not appear to give a satisfactory result for NGC 7027. For example, the Clegg-Middlemass model for $T(^*) = 180{,}000$ predicts He II 4686 Å too strong and [Ne V] too weak (simply raising the temperature above 180,000 K does not seem to help much). The usual assumption that the composition of the stellar surface layers matches that of the nebula may not always be valid. The nebular composition may be nearly "normal", i.e., approximately solar, but H and He may be severely depleted in the PNN so that we need stellar models in which the principal sources of opacity are C, N, O, Ne, etc. Emergent radiative fluxes for a family of such atmospheres have been calculated by Hubeney (1989) and will be discussed in a separate communication, but even with these atmospheric fluxes the [Ne V]/λ4686 ratio is not yet properly explained. Further adjustments or refinements would appear to be needed.

One procedure has been to modify empirically the radiative flux beyond 7.2 Rydbergs in a standard model in order to enhance the production of [Ne V].

Our finally adopted model nebula had a central star with a radius of 0.07 $R_\odot$, an essentially hollow shell of internal radius 0.009 pc, and an outer (Strömgren sphere radius) of 0.0128 pc. The best fit to the observations was obtained with a truncated radius of 0.0124 pc with an optical depth at the Lyman limit of 53. The H density at the inner surface was taken as 80,000 and assumed to fall off as the inverse square of the distance from the central star. The stellar radiative flux somewhat resembles that proposed by Mazzalli (1989) for the energy distribution in the hotter component of β Lyrae. Such an ultraviolet excess was attributed to a stellar wind. Another example of a probable strong UV excess in the emergent radiant flux from an early type star is the appearance of unusual, enhanced stellar wind features in the spectrum of the B0 V star τ Scorpii (Walborn *et al.* 1985).

Table 7 compares the observed intensities with the predicted values obtained for a shell with a truncation radius of 0.0124 pc and for a full Strömgren sphere $r = 0.0128$ pc. The theoretical model predicts smaller average excitation temperature differences than are indicated by the diagnostic diagram; e.g.,

$$T([\text{Ne IV}]) - T([\text{O III}]) \simeq 2000 \text{ K (observed)}$$
$$\simeq 900 \text{ K (predicted)} .$$

TABLE 6

Ionic Concentrations

Ion	λ	I_{CORR}	T_ε	N_ε	$\frac{N(ion)}{N(H^+)}$	$\sum\frac{N(ion)}{N(H^+)}$
He I	(See text)		14,000	50,000	0.058	0.111
He II			16,000		0.053	
C III	1907, 1909	927	14,000	60,000	2.58(-1)	5.2 (-4)
C IV	1548, 1550	1518	14,000	60,000	2.63(-4)	
N I	5198, 5200	0.43	14,000	30,000	1.0 (-6)	
N II	6548, 6584	132.6	14,000	35,000		
	5755	5.57		35,000	1.23(-5)	
N III	1747-1754	36.5	14,000	30,000	4.3 (-5)	1.18 (-4)
N IV	1483-1487	59.7	15,000	60,000	5.0 (-5)	
N V	1239, 1243	41.0	16,000	60,000	1.31(-5)	
O I	6300, 6363	14.1	14,000	60,000	7.0 (-6)	
O II	3727	24.1	14,000	64,000	2.5 (-5)	
	7319, 7330	27.6				
	2470	30.0	14,000	64,000	3.6 (-5)	
O III	4959, 5007	1878	14,000	64,000	2.09(-4)	2.34 (-4)
	4363	25.4	14,000	64,000	1.9 (-4)	
	1658, 1666	42.5	14,000	64,000	< 2.7 (-4)	
F IV	3997, 4060	0.15	16,000	64,000	1.6 (-8)	1.6 (-8)
Ne III	3868, 3967	156.6	14,000	64,000	3.72(-5)	
Ne IV	2423, 2425	103.4	16,000	57,000	2.46(-5)	
	4724-4726	3.30	16,000	57,000	2.44(-5)	9.35 (-5)
	1602	18.5?			3.48(-5)	
Ne V	3346, 3426	205	16,000	60,000	3.18(-5)	
Na IV	3341, 3362	2.0	15,000	60,000	6.9 (-7)	6.9 (-7)
Mg II	2796, 2803	23.4	14,000	30,000	0.17(-6)	6.6 (-6)
Mg V	2784, 2927	14.5	15,000	60,000	6.6 (-6)	
Si III	1884, 1892	30.3	14,000	64,000	2.03(-6)	2.0 (-6)
Si IV	1394-1403	< 67.5	14,000	64,000	< 1.12(-6)	
P II	4669.2	0.155	14,000	30,000	6 (-6)	6 (-6)
	7876					
S II	6717, 6731	5.41	14,000	40,000	3.6 (-7)	
	4068, 4076	8.9	14,000	40,000	4.1 (-7)	2.7 (-6)
S III	6312	3.8	14,000	30,000	2.30(-6)	
	9069, 9552	114	14,000	30,000	2.32(-6)	

TABLE 6 (Continued)

Ion	λ	I_{CORR}	T_ε	N_ε	$\frac{N(ion)}{N(H^+)}$	$\sum\frac{N(ion)}{N(H^+)}$
Cℓ II	8579	0.25	14,000	30,000	1.33(-8)	
Cℓ III	5517, 5537	0.81	14,000	80,000	5.51(-8)	
	3353	0.21	14,000	80,000	5.97(-8)	1.17 (-7)
	8433, 8481	0.15	14,000	80,000	5.05(-8)	
Cℓ IV	7530, 8045	1.76	15,000	80,000	5.07(-8)	
	5323	0.094	15,000	80,000	5.1 (-8)	
Ar III	7135, 7751	26.8	14,000	50,000	9.9 (-7)	
	5192	0.27	14,000	50,000	9 (-7)	
Ar IV	4711, 4740	12.53	15,000	52,000	5.2 (-7)	1.73 (-6)
Ar V	6435, 7005	5.3	16,000	52,000	2.2 (-7)	
	4625	0.12			2.2 (-7)	
K IV	6103	0.47	15,000	40,000	5.0 (-8)	
K V	4122, 4163	0.38	15,000	40,000	5.4 (-8)	1.22 (-7)
K VI	5604, 6228	0.075	16,000	40,000	1.8 (-8)	
Ca V	5309	0.300	16,000	40,000	6.4 (-8)	6.4 (-8)

I_{CORR} = interstellar reddening-corrected line intensity

Poor predictions are obtained for neutral and singly ionized atoms which would be concentrated in dense, partly ionized blobs that are not handled with models of smoothly varying density. All the models tended to predict He II lines that were too strong compared with [Ne IV] and [Ne V]. If we adjust n(Ne)/n(H) to fit these Ne ions, [Ne III] is much too strong and the [Ar III] lines are too strong if [Ar IV] λ4711, λ4740 and [Ar V] λ6435 and λ7005 are reasonably well represented. The chlorine ionization pattern is better handled. [S II] line ratios are badly represented with $N_e = \sim 80{,}000$ cm^{-3}. The models do not give good bases for deriving reliable ICF's for F, Mg, P, and Si. For these ions we use empirical ICF's guided essentially by the behavior of data for N and O.

Estimation of the ionic concentration of He I is complicated by the situation that the normally used lines, λ5876, λ6678, and λ4471, originate from levels that are populated not only by recombinations from the continuum but also by collisional excitation from the metastable level 2^3S. Therefore, it is important to know what fraction of the helium atoms reaching 3^3D, 4^3D, and 3^1D do so by collisional processes. The fraction depends on T_e, the number of atoms in 2^3S, and appropriate collisional cross sections. Implications of observational data are discussed by Brocklehurst (1972), Barker (1978), and Peimbert and Torres-Peimbert (1987*a*). Recent theoretical discussions are by Ferland (1986), Clegg (1987), and Peimberts (1983), and by Clegg and Harrington (1989).

Clegg gives convenient formulae whereby the ratio of excitations by collisions to those by recombination, C/R, may be calculated as a function of T_e and N_e. The effects are quite important in NGC 7027. Without these corrections, our line intensity values for λ6678, λ5876, and λ4471, corrected for interstellar extinction, yield $N(He^+)/N(H^+)$ = 0.0705, 0.0864, and 0.6708, respectively. With the Clegg C/R values computed for N_e = 63,000, T_e = 14,000 K, we obtain 0.059, 0.057, and 0.058. There is some evidence that the 2^3S level may be underpopulated. If we take $\gamma = N(2^3S)_{obs'd}/N(2^3S)_{pred} \simeq 0.6$ (cf. Peimbert and Torres-Peimbert 1987*a*,*b*; Clegg and Harrington 1989), then $\langle N(He^+)/N(H^+)\rangle = 0.063$ and the total He/H ratio is 0.116 instead of 0.111. We adopt the lower values in Tables 6 and 8. The He/H ratio is increased by 0.002 if we use N_e and T_e values recommended by Péquignot and Baluteau.

Recently, Gruenwald and Péquignot (1989) proposed a model for NGC 7027 which supplants an earlier effort by Péquignot, Aldrovandi, and Stasinska (1978). They find

TABLE 7

Detailed Comparison of Predicted and Observed Line Intensities

λ	ID	I_{CORR}	Predicted I, r = 0.0124	Predicted I, r = 0.0128
4471	He I	3.32	2.4	2.6
5876	He I	10.85	6.2	6.9
4686	He II	48.4	54.1	52.3
4267	C II	0.57	0.29	0.29
1907	C III	354	389	382
1909	C III	573	718	702
1548	C IV	956	987	953
1550	C IV	562	499	482
5198	[N I]	0.27	0.042	
5200		0.16	0.024	
6548	[N II]	34.3	32.4	44.6
6584		98.3	96.5	133
5755		5.57	6.7	8.4
1747-1754	N III	36.5	61.4	59
1483-1487	N IV	59.7	53.1	51.3
1239/1243	N V	41	43	42
6300/6363	[O I]	14.1	2.8	11.6
3726	[O II]	17.7	18.8	26.7
3729		6.4	6.8	9.7
7319		15.2	12.9	16.2
7330		12.4	10.4	13.1
4959	[O III]	478	515	499
5007		1400	1491	1445
4363		25.4	31.1	30.1
1658/1666	O III	42.5	63	61
1394-1407	O IV	<67	45	43.6
3868	[Ne III]	117.2	160	165
3967	[Ne III]	39.4	47.8	49
3342.15	[Ne III]	1.07	0.68	0.69
2423	[Ne IV]	78	43.6	42.1
2425	[Ne IV]	25.4	12.1	11.7
4724.3	[Ne IV]	1.11	0.63	0.60
4725.7	[Ne IV]	0.91	0.55	0.53
3345.9	[Ne V]	52	31.6	30.5
3426	[Ne V]	153	85.6	52
3241	[Na IV]	1.53	0.98	0.94

λ	ID	I_{CORR}	Predicted I, r = 0.0124	Predicted I, r = 0.0128
2796,2803	Mg II	23.4	44	57
6717	[S II]	1.64	1.0	1.9
6731		3.77	1.8	3.4
4068.7		6.74	5.9	8.7
4076.2		2.16	5.8	8.6
6312	[S III]	3.77	4.5	4.5
9069		33	36.4	36.8
9552		80.5	90.3	91.2
8579	[Cℓ II]	0.25	0.19	0.27
5517	[Cℓ III]	0.19	0.16	0.16
5537		0.62	0.56	0.57
3353.3		0.21	0.35	0.35
7530	[Cℓ IV]	0.54	0.54	0.52
8045		1.22	1.2	1.2
5323		0.094	0.090	0.84
7135	[Ar III]	21.3	15.6	16.6
7751		5.5	3.7	3.9
5192		0.27	0.22	0.23
4711	[Ar IV]	2.83	3.0	2.9
4740		9.70	11.6	11.2
7171		0.59	0.36	0.35
7237	[Ar IV]+C II	0.72	0.28	0.26
7263	[Ar IV]	0.47	0.29	0.28
6435	[Ar V]	1.57	1.5	1.5
7005		3.73	3.2	3.1
4625		0.11	0.10	0.10
6103	[K IV]	0.47	0.57	0.59
4122	[K V]	0.10	0.085	0.081
4163		0.28	0.10	0.095
5604	[K VI]	0.03	0.006	0.007
5309	[Ca V]	0.30	0.26	0.25

$T(^*) = 200{,}000$ K, $\langle N_e \rangle \sim 70{,}000$ cm^{-3}, with $\langle T_e \rangle$ showing a considerable range as noted above.

Table 8 gives our final abundance determinations. The second column lists the sum of the ionic concentrations for the elements listed in the first column. The third column lists the ICF calculated from our model number 19 at the truncation radius of 0.0124 pc, $\tau_{H\,I} = 52.6$. The fourth column gives N on the scale $N(\mathrm{H}) = 1.0$. It is calculated by multiplying the entries in the second column by the ICF's in the third column. The fifth

TABLE 8

Chemical Composition of NGC 7027 Compared With the Sun

Element	$\sum \frac{N(X_i)}{N(H^+)}$	ICF	N ICF Method	Model 19	Δ	N(☉) Grevesse and Anders
He	0.111	1.00	0.111	0.11		0.098
C	5.2 (-4)	1.33	6.9 (-4)	6.0 (-4)	+ 0.06	3.6 (-4)
N	1.18 (-4)	1.06	1.25 (-4)	1.50(-4)	- 0.08	1.12 (-4)
O	2.34 (-4)	1.32	3.1 (-4)	3.0 (-4)	+ 0.01	8.5 (-4)
F	1.6 (-8)		8 (-8)			3.5 (-8)
Ne	9.35 (-5)	1.07	1.0 (-4)	9.5 (-5)	+ 0.02	1.17 (-4)
Na	6.9 (-7)	4.4	3.0 (-6)	2.0 (-6)	+ 0.18	2.14 (-6)
Mg	6.6 (-6)	4.0	2.6 (-5)	5.0 (-5)		3.62 (-5)
Si	2.0 (-6)	3	6 (-6)	5.0 (-6)		3.54 (-5)
P	6 (-6)	5	3 (-6)			2.8 (-7)
S	2.7 (-6)	2.4	7.1 (-6)	6.9 (-6)	0.00	1.62 (-5)
Cℓ	1.17 (-7)	1.71	2.0 (-7)	1.8 (-7)	0.05	3 (-7)
Ar	1.73 (-6)	1.23	2.1 (-6)	2.0 (-6)	0.03	3 (-7)
K	1.22 (-7)	1.20	1.48 (-7)	1.6 (-7)	- 0.03	1.32 (-7)
Ca	6.4 (-8)	5.9	3.8 (-7)	4.0 (-7)	- 0.02	2.3 (-6)

N is expressed on the scale $N_H = 1.0$.

column gives the N-values actually employed in model No. 19. The sixth column gives $\Delta = \{\log N(\text{ICF method}) - \log N(\text{model 19})\}$. The seventh column gives the solar abundances based on the work of Anders and Grevesse (1989).

The abundance pattern for NGC 7027 resembles that of many other planetaries. Carbon is enhanced by a factor of 2. The progenitor of NGC 7027 probably was a carbon star of intermediate mass, most likely in the $2\,\mathfrak{M}_\odot$–$5\,\mathfrak{M}_\odot$ range (Iben 1988). The N abundance is close to "normal", while O is depleted by a factor of about 2.7. If the mass were high we would expect the N/O ratio to be high (Becker and Iben 1980; Peimbert 1978). Neon lies close to the standard solar, local galactic values, as do probably also Na, Mg, and K, whose abundances, however, are more uncertain. S would appear to be depleted by about a factor of 2.7 with respect to the Sun, while Cℓ and Ar may be below the solar abundance by a factor of about 1.7. As noted in earlier work (e.g., Aller 1978), Ca is depleted by a factor of about 6. Presumably, it is tied up in grains as is also probably Fe (Shields 1978). The chemical composition of NGC 7027 appears to show none of the exotic characteristics of objects such as NGC 6537 (Feibelman *et al.* 1985) or Peimbert's Type I N-rich objects; rather, it appears to resemble Peimbert's Type II (1978).

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