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HIGH DISPERSION SPECTRA FOR PLANETARY NEBULA STUDIES

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RESUMEN

Mapas de alta resolución en radio, imágenes directas con el *Telescopio Espacial Hubble* y observaciones con grandes telescopios con óptica adaptiva muestran que las nebulosas planetarias tienen formas extremadamente complicadas y son muy diferentes de la simplicidad con que se las imaginaba tiempo atrás. Para atender este problema, uno debe obtener espectros con alta resolución espacial y alta dispersión. También se requieren largos tiempos de exposiciones, aún con telescopio grandes, para observar las estructuras débiles. Basados en nuestro trabajo de alta dispersión revisamos brevemente el diagnóstico del plasma y a posibilidad de utilizar iones de hierro para este diagnóstico.

ABSTRACT

The extremely complicated shapes of planetary nebulae revealed through the high resolution radio maps, direct imaging with the *Hubble Space Telescope* and observations with adaptive optics at large telescopes, are greatly different from their imagined simplicity long ago. To address the complexity in physical conditions and geometries of planetary nebulae, one must secure spectra of high spatial resolution and high dispersion. It also may require a long exposure even with a large telescopic aperture to reach faint features. We briefly review plasma diagnostics and a diagnostic possibility of iron ions based on our recent high dispersion spectroscopic work.

Key Words: **ATOMIC DATA — PLANETARY NEBULAE — TECHNIQUES: SPECTROSCOPIC**

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1. INTRODUCTION

Recent studies of planetary nebulae (PNs) with high resolution radio maps, direct imaging with the *Hubble Space Telescope*, *HST*, and observations with adaptive optics at large telescopes clearly have shown planetary nebulae to be often fantastically complicated, exotic objects. There were inadequate clues to this fact many years ago.

Long ago, Curtis (1918) completed the first photographic survey with the 36″ Crossley Reflector at Lick Observatory and found that although many objects appeared orderly, there were irregularities, blobs, and ansae indicative of a more complex structure. Unfortunately the scale of the Crossley was too small and the effects of bad seeing were too large to give more than tantalizing suggestions for many objects. The next big advance was achieved by Minkowski who obtained monochromatic direct images with the Palomar 5-meter Telescope and by Olin Wilson who secured high dispersion slitless spectrograms with an image rotator at the coude focus of the Mount Wilson 2.5-m reflector. The extremely intricate, broken structure of both the inner and outer rings of NGC 2392, the "Eskimo" Nebula, for example, as secured by Minkowski and by Wilson are reproduced in Aller (1956, Fig. VII. 12).

For most Planetary nebulae, many of us felt somewhat comfortable with the simple theoretical model of Sun Kwok—a roughly spherical shell derived from the outer envelope of the highly evolved AGB star bulldozed by the rapidly moving spherically symmetric wind from the central star, setting up shock waves running outward through the cool AGB shell and inwards back towards the hot core—but, alas many PNs exhibit structures reminiscent of celestial whirling debris rather than fundamentally orderly structures.

What one needs is extremely high spatial resolution, better than a fraction of a second of arc. This is difficult to achieve in ground based optical observations, and we have to rely on radio-frequency, *HST*, or adaptive optics observations.

Studies of particularly highly intricate objects such as the "proto-type" N-rich Peimbert Type I PN, NGC 2440, are especially engaging. This planetary originally described as a "classical" bipolar PN is actually an extremely complex polypolar object (López et al. 1998). These authors remark that "several bipolar structures are shown to be emerging at different position angles from the core, as expected from bipolar, rotating, episodic outflows with different degrees of collimation." Various scenarios involving binary stars with accretion disks, MHD models with magnetized winds are involved in some of the more

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promising scenarios that have been proposed (see, e.g., García-Segura, Franco, & López 2000; Reyes-Ruiz & López 2000).

Thus, as the scope of our observations increases, the true complexity of the phenomena we are studying is revealed. The simple idea of a spherical shell surrounding a hot star is unsatisfactory. It may be useful as a zeroth order, initial photo-ionization model, which hopefully can represent the distribution of atoms among various ionization stages, but it will not give necessarily the correct electron temperature, T_e. Nor will it give the correct fluctuation or spread in electron temperature throughout the PN. Peimbert (1967) gave a method for calculating the mean square fluctuation of T_e throughout the radiating layers of a gaseous nebula. This is an important quantity to take into account in evaluating chemical compositions or other nebular parameters. It has been always found the temperature fluctuation predicted by the photoionization model to be less than that found from the Peimbert analysis which seems much closer to the truth. Why? The photoionization model does not take shock waves into account and these always act to boost and increase spread in T_e. We are led to suspect that in a real PN a variation in T_e may sometimes exist that may be considerably greater than that given by photoionization models (Peimbert, Luridiana, & Torres-Peimbert 1995).

2. CHALLENGE TO THE SPECTROSCOPIST

The extreme structural complexity of PN is a far cry from their imagined simplicity some 80 or 90 years ago. Their spectra must reveal some of this intricacy. Actually, we take a slice through a melange of jets and shells and obtain an averaged spectrum which reflects the combined contributions of contributing volume elements with their different densities and temperatures. These will be revealed by the appropriate diagnostics. Thus one wishes to use a number of such criteria.

For this study we have used the Hamilton echelle spectrograph on the 3-m Shane telescope at Lick Observatory. We cover the range 379 to 1005 nm. We use a 640 μm slit which amount to 1.2$''$ at the coude focus. For a slit width of 640 μm, the limiting resolution of the CCD chip is about 1.75 pixels and 2 pixels would be about 0.05 Å at 360 nm and 0.15 Å at 885 nm. Because of overlapping orders a slit length of 4$''$ is used. Thus one observes a pencil beam through the PN. Hyung (1994) has described the observing procedure—the use of arcs, flat-fields, and comparison stars that are required for practical observations. With other arrangements such as a traditional coude spectrograph one can use long slits. What is required for a detailed study of a spectrum are high spectral resolution and the ability to reach faint features in the spectrum. As our studies of PN grow more inclusive and demanding so do the requirements of our observing. We will choose two examples: Plasma diagnostics and the spectra of various iron ions.

2.1. *Plasma Diagnostics*

With a big spread in electron densities and temperatures, N_e and T_e, in the radiating layers, much larger than that anticipated from photoionization models we would like to have a variety of criteria for different temperatures and densities. Originally, only [O III] which gave primarily T_e, and [O II] which gave a clue to N_e were available. Another important factor is that there has been great progress on the observational front. Initially, our efforts were confined to the optical region, from 310 nm to the near IR. But now with the International Ultraviolet Explorer we can reach to the Lyman cut-off just to the redward of 91.2 nm. The accessible infrared is important because it enables us to observe lines connecting low-lying levels in terms of equivalent p- and d-electrons. This can give significant clues to the density of the gas.

Most of the ions used for diagnostic studies in planetary nebulae involve equivalent p-electrons: p^2 as in [O III]; p^3 as in [S II] or [O II]; and p^4 as in [Ne III]. The A-values and collision strengths for the forbidden lines of p^2 and p^4 can be calculated with moderate accuracy without such difficulty and yield atomic parameters useful for obtaining electron temperatures. Since we compare the auroral or transauroral type transitions (which always have the highest excitation potential with the lower lying levels of the nebular transitions), the temperature determination is always biased towards the hottest strata (see, for example, the discussions by Peimbert et al. 1995).

With the forbidden lines of the p^3 we can get both T_e and N_e for the same emitting layers. For example, the 3726/3729 line ratio of [O II] depends primarily on electron density, but if we observe also the auroral transition 7319 and 7330, we can use the ratios of the intensity 7319+7330 to 3726+3729 and the 3727/3729 ratio to get two numbers, one of which depends almost entirely on N_e and the other on both N_e and T_e. Thus, for a single ion we can get both N_e and T_e, tying the plasma diagnostics down for a single point. The temperature does not have as high a precision as temperatures gotten from the ratios of auroral to nebular lines of a p^2 or p^4 configuration. To get both N_e and T_e for [O III] we would need both

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4363/5007 and data on the infrared fine structure lines as well as on space absorption, while the p^3 configuration often allows us to get the diagnostics from lines in the same spectral region.

Until recently it has proven very difficulty to obtain complete collision strengths for p^3 configuration. Thanks particularly to the efforts of the Belfast group, we now have the relevant parameters for the ions: [S II], [O II], [Ne IV], [Cl III] and [Ar IV]. See Keenan et al. (1995 et seq.).

3. DIAGNOSTIC CRITERIA

3.1. p^3 *Configurations*

The intricate structures of PN requires that on the one hand we obtain as high resolution imaging as possible, preferably in the monochromatic radiations of ions of greatly differing excitation, e.g., [O III], [Ne V], He II, H I, [O II], [O I], and [S II]. Simultaneously, we should try to obtain as many diagnostics as possible to get T_e and N_e in the various radiating strata. Table 1 compares T_e values obtained from p^3 configurations with that found from [O III] and from [O I].

Some PNs such as NGC 2440 suggest a hot [Ne IV] and [O III] zone; NGC 7662 seems to be relatively isothermal. The high excitation shell of NGC 7009 has a higher temperature than the low-excitation cool region at the end of the major axis 12 000 K vs. 6800 K. Some of the T_e discrepancy may arise from observational errors. Yet a large spread in T_e seems real; and this may have a profound effect on abundance determinations. For example, Peimbert et al. (1995) recommend we use T_e found from C III rather than that from the [O III] lines to compute the abundance of O^{++}. The difference is often quite large. Should an analogous correction be applied to T([C III]) and other ions? In other words, must we derive corrections to *all* temperature determination from forbidden lines?

3.2. *Abundance Determination*

Abundance determinations of elements in gaseous nebulae was hindered in the early days by our ignorance of fundamental atomic parameters, especially collision strengths. The general outline of attack was proposed in 1945 and applied to PNs observed by Wyse (1942). Not much progress could be made until collision strengths were available from the work of Seaton (1954). An analysis of the then available data (Aller 1956) suggested that some objects such as NGC 2440 and NGC 6741 were abnormally rich in N. Peimbert (1978) distinguished between different composition types of PN, of which the most striking was his type I which presumably originate from the most massive stars that are capable of evolving into PN. A great deal more will have to be known about the structure and evolution of PN before we can determine their chemical compositions with the precision we believe we have for stars such as the Sun. Aside from the aforementioned complications arising from the structural and kinematics details, there is also the fact that in some PN the chemical composition actually varies from one part of the shell to another, e.g., Abell 30.

One of the factors that greatly hindered the study of abundances in PN in the 40's and 50's was the persistent dogma of the universal uniformity of compositions of stars and nebulae. Heretics who refused to buy this assertion found themselves disadvantaged.

4. SOME REMARKS ON THE IRON ION SPECTRA OF PLANETARIES

Many celestial sources such as η Carinae, supernova remnants, and especially active galactic nuclei (AGNs) and quasars display prominent spectra of iron ions, especially Fe II (cf. Viotti 1988), and PNs show some iron ionic lines. They are not particularly strong, whilst lines of elements of comparable abundance such as S or Mg are much more prominent. Sulfur has a $3p^4$ configuration as its ground state. In iron there seems to exist a competition between the 3d- and 4s-electrons as to which is the more tightly bound. In effect, several low configurations have very nearly the same energy and interact in a complicated fashion. Configurations like $3d^6\,4s$ produce many terms which result in numerous lines which for Fe II largely fall in the 1500–4000 Å region, (hence the "iron forest") in the spectra of QSOs. These Fe II lines are excited by radiation, from electronic collisions, and recombinations but radiation, those around 7 eV are largely excited by fluorescence (Netzer 1988; Netzer & Willis 1983; Nave & Johansson 1993).

In PN the [Fe $\cdots$] lines are unexpectedly weak as we note below. Probably the Fe is tied up in grains, as appears to be the situation with diffuse nebula. In Orion, Rubin et al. (1997) suggest Fe is depleted ten times with respect to the Sun in one of the hottest regions. The same situation appears to obtain in planetaries, where Shields was the first to look into the problem.

It has long been known that the spectra of PN show weak lines of Fe ions from Fe II to [Fe VII] with intensities up to 0.3 or even 1.00 on the scale $I(4861) = 100$, although most of the detectable lines are usually 0.1, 0.2, or even less. We measured iron ion lines in the spectra of IC 351, IC 418, NGC 2440,

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TABLE 1

ELECTRON TEMPERATURES IN SOME REPRESENTATIVE NEBULAE

Nebula	[O I]	[S II]	[O II]	[Ar IV]	[Ne IV]	[O III]
IC 419		7 500	10 670			9800
NGC 2440	11 500	12 500	11 750	11 750	19 800	14 400
IC 2165			9 750		21 500	12 200
NGC 6572	11 000	12 950	16 500[a]	11 700		11 000
NGC 6741	11 300	9 650	11 750	13 050		12 500
NGC 6790		11 750	8 500			10 900
NGC 6818			19 000[a]		13 500	11 400
NGC 6884			11 750	12 300		10 000
NGC 7009	11 500	12 400	11 750	12 500		12 500,6800
NGC 7027			19 300[a]	18 200	19 980	14 000
NGC 7662			12 000	12 900		12 500

[a]These are likely involved with errors of atomic constants or observations.

NGC 6537, NGC 6543, NGC 6572, NGC 6741, NGC 6790, NGC 6818, NGC 6884, NGC 6886, NGC 7009, NGC 7027, NGC 7662, IC 4846, IC 4997, BD+30 3639, and Hb 12. We found Fe ion lines in all these PN although they were extremely weak in some objects. Some PN such as NGC 40 and NGC 6741 also show a number of iron ion lines.

A determination of the Fe abundance is tricky. Not only are there a large number of possible ionization states, but much of the iron may reside in solid grains and not be observable at all. Still, in some PN iron may exist almost all in the gaseous stage. An example may be Westerlund-Smith 25 in the LMC where [Fe VI] and [Fe VII] are unusually strong (Aller & Czyzak 1983).

Note that with equivalent d-electrons there are diagnostic possibilities greater than exist for equivalent p-electrons. Possibilities occur for [Fe II] but consider, for example, [Fe VII], where the fluorescent excitation spectral lines plays a very important role (Chen & Pradhan 2000). By radiative pumping, atoms are raised from the ^{4}F ground level of Fe VII to ^{4}D$_0$, ^{4}F$_0$, and ^{4}G$_0$ levels from which they cascade to an intermediate level, ^{4}P from which they descend to the ground level with the emission of optical lines. Of course atoms can also be excited to the intermediate ^{4}P level by collisions and to a lesser degree by direct capture from the continuum. In optimum situations, we can set constraints on N_e, T_e, $T_\star$, r, and $W(r)$, where N_e and T_e are the electron density and temperature as usual, $T_\star$ describes the energy distribution in the stellar spectrum, and r is the distance from the star to the radiating volume. One can use the observed intensities of the lines in conjunction with the appropriate equations to solve the expressions for the plasma diagnostics, the size of the radiating region and get a fix on the stellar temperature.

The dense, low excitation PN IC 4997 shows [Fe III] prominently (Keenan et al. 1993) largely in the 4607–5412 Å range. The relative populations of the 17 fine-structure ^{5}D, ^{3}P, ^{3}H, ^{3}F, and ^{3}G terms of the 3d^6 ground configuration depend on N_e and T_e in such a way as to give good diagnostics. These lines are more useful in combination variables such as Z And or CI Cygni. At high excitations [Fe VII] is very useful (Keenan & Norrington 1991). Given an estimate of N_e, we may evaluate T_e from the 4945/5721 and 5159/5721 ratio. Of iron ions, Fe II is especially interesting (Viotti 1988).

5. SOME CONCLUDING REMARKS

We must, again, emphasize that to use these methods successfully we must have spectroscopic data of high accuracy and spectral resolution. To fully exploit the advantages, they must be supplemented by good spatial resolution. In fact the future of PN spectroscopy depends on (a) a wide wavelength coverage from the infrared to the ultraviolet, (b) data with good imaging, such as is attainable with the *HST*, or adaptive optics techniques that are now becoming available and (c) monochromatic imaging. An attempt should be made to explain the nebula via a theoretical model, an endeavor that may be successful only for rather simple objects. Complex polypolar objects such as NGC 2440 are probably beyond our capabilities at the present time, but ultimately we will have to resort to models. We must take into account also the changes required by the zone of neutral atoms and molecules (Kwok 1999).

Possibly, at this stage it may be well to draw up a list of target objects. We propose a few candidates, many of them classical objects extensively studied in the past but also young objects which are evolving before our eyes. A number of these PNs come easily to mind. Our task is to construct for such objects complete models reproducing their spectra, structure, kinematics, and probable evolutionary histories. Intrinsically very luminous NGC 7027 with its high density and rich spectrum has perhaps the most to offer. NGC 6302 has an interesting structure and rich spectrum, while NGC 7662 seems more amenable to modeling. These are among the most intensively observed objects; they put firm constraints on the models.

NGC 7027 has been examined in many spectral regions. It may lie near the maximum of PN luminosity; its central star may have been very massive, and the total mass of the PN may be near the upper limit. It has one of the highest intrinsic surface brightness and highest densities known among PN. Thus it is not surprising that it has perhaps the richest PN spectrum known. For a description of the optical spectrum, see, e.g., Keyes, Aller, & Feibelman (1990) and references therein. NGC 6302 is another object with an interesting structure and rich spectrum (see Aller et al. 1981 and references therein). Perhaps our efforts should start with a more regular object such as NGC 7662 (Harrington et al. 1982), more amenable to theoretical modeling. The reason for concentrating on these better known objects is that relevant observational data are more complete so that stricter constraints may be put on the models and a more complete picture obtained. Of equal importance may prove the modeling of objects such as M2-9 which may be fruitful in tracing the intricate evolution of complicated PN. We certainly have our work laid out for us.

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