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Infrared Emission Lines in Planetary Nebulae

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      emission lines in planetary nebulae. Measurements of these lines offer
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INFRARED EMISSION LINES IN PLANETARY NEBULAE

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ABSTRACT

Advances in infrared spectroscopy have led to the detection of many forbidden fine-structure emission lines in planetary nebulae. Measurements of these lines offer sensitive probes of the physical conditions and ionization structure, and lead to improved abundance determinations. This paper reviews recent observations and discusses the ways in which infrared line measurements can contribute to our knowledge of planetary nebulae.

I. INTRODUCTION

Infrared fine-structure emission lines have unique properties which make them useful tools for studying the physical conditions, ionization structure, and chemical abundances in planetary nebulae. These forbidden transitions fall into two categories: (1) lines arising from the single ground-state transition of p^1 and p^5 ions and (2) lines arising from the triplet ground term of p^2 and p^4 ions (see Fig. 1). Lines of the first category offer the opportunity to sample ions that are usually unobservable in other spectral regions. They can be used to study the ionization structure of nebulae and, in combination with other ions of the same elements, to derive better total abundances. As indicated in Figure 1, p^2 and p^4 ions have optical or UV transitions connecting the ground term and higher terms of the same electron configuration, as well as infrared transitions among levels of the ground term. The fine-structure line emissivities have very different dependences on physical conditions than do the optical lines of the same ion. As a result, observations of lines in the second category make it possible to analyze in detail the electron temperature and density, and variations in these parameters within a nebula. Such studies are important not only in understanding the density and ionization structure, but also strongly influence abundance determinations, which depend on the assumed physical conditions.

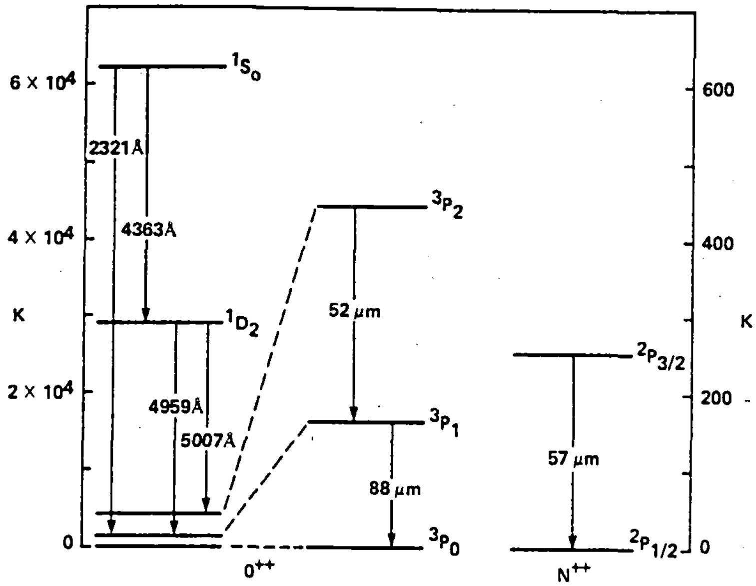

Figure 1. Energy-level diagrams are shown for the ground electron configurations of O III and N III. The vertical axis is the excitation energy in units of degrees Kelvin, hν/k. The O III ion is representative of the p^2 configuration, and N III is an example of the two-level p^1 and p^5 configurations.

The theory describing the emission of forbidden lines has been presented by many authors (e.g., Osterbrock 1974), the infrared fine-structure lines in particular have been discussed by Simpson (1975). Many of the recent observations described in this review have been made possible by the development of moderate-to-high spectral resolution infrared spectrometers and their use on the Kuiper Airborne Observatory, as well as on ground-based telescopes. Descriptions of some of these instruments can be found in Soifer and Pipher (1978) and in references cited below.

II. DETECTION OF NEW LINES AND IONS

The 8-14 μm window, observable from the ground, offers three major fine-structure lines: Ar III 9.0 μm, S IV 10.5 μm, and Ne II 12.8 μm. These lines were first detected in planetary nebulae about 12 years ago (see Rank 1978), and recent observations of them will be discussed below in Section IV. Since then, the availability of a low water-vapor platform, the Kuiper Airborne Observatory, has opened up the spectral regions 5-8 μm and 16-100 μm. This has enabled the detection of a variety of ions both of very high and very low ionization potential, many of these measured first in the bright, complex planetary NGC 7027. Some of these lines have made it possible to observe important ions for the first time.

The low-resolution 4-8 μm spectrum of NGC 7027 taken by Russell et al. (1977) showed, in addition to broad, dust-related features, several emission peaks which they attributed to ionic lines. Recent higher spectral resolution observations by Beckwith et al. (1982) have confirmed the presence of the Mg IV 4.5 μm and Mg V 5.6 μm lines (see Table 1), which indicate a large amount of magnesium in these very highly ionized species. Two other high-ionization lines, O IV 25.9 μm and Ne V 24.3 μm, have been measured by Forrest et al. (1980). They also find that large fractions of the respective elements are in the form of these highly ionized species. The relative intensities of Ne V 24.3 μm and 3426 Å are consistent with $T_e = 12,500$ K and $n_e = 2.5 \times 10^5$ cm^{-3} in the Ne V-emitting zone, within the uncertainty in the extinction correction in the blue. For these conditions, Forrest et al. derive $Ne^{+4}/H^+ \sim 10^{-4}$ and $O^{+3}/H^+ \sim 4 \times 10^{-4}$.

TABLE 1

INFRARED LINES MEASURED IN PLANETARY NEBULAE

Ion	λ (μm)	Transition	I.P. Range (eV)
Mg IV	4.49	$^2P_{3/2} - {}^2P_{1/2}$	80.1 - 109.3
Mg V	5.61	$^3P_2 - {}^3P_1$	109.3 - 141.3
Ni II	6.62	$^2P_{1/2} - {}^2P_{3/2}$	7.6 - 18.2
Ar II	6.98	$^2P_{1/2} - {}^2P_{3/2}$	15.8 - 27.6
Ar III	8.99	$^3P_1 - {}^3P_2$	27.6 - 40.7
S IV	10.52	$^2P_{3/2} - {}^2P_{1/2}$	34.8 - 47.3
Cl IV	11.76	$^3P_1 - {}^3P_2$	39.6 - 53.5
Ne II	12.81	$^2P_{1/2} - {}^2P_{3/2}$	21.6 - 41.0
S III	18.71	$^3P_2 - {}^3P_1$	23.3 - 34.8
Ne V	24.28	$^3P_1 - {}^3P_0$	97.1 - 126.2
O IV	25.87	$^2P_{3/2} - {}^2P_{1/2}$	54.9 - 77.4
O III	51.81	$^3P_2 - {}^3P_1$	35.1 - 54.9
	88.36	$^3P_1 - {}^3P_0$	
N III	57.33	$^3P_{3/2} - {}^3P_{1/2}$	29.6 - 47.5
O I	63.17	$^3P_1 - {}^3P_2$	0 - 13.6

Other p^1 and p^5 ions, observable only by means of their fine-structure lines, are dominant species in nebulae ionized by very cool stars. Ne II, mentioned above, is one example. More recently, Ar II 6.98 μm has been measured in IC 418 (Willner et al. 1979) and BD+30°3639 (Dinerstein et al. 1982). Since the Ar II ion has an ionization potential similar to that of neutral helium (which is not directly observable), measurements of Ar II may prove to be useful for understanding the ionization and abundance of helium in gaseous nebulae, as well as in determining argon abundances.

Emission lines from ions with ionization potentials lower than that of hydrogen (13.6 eV) may be expected to arise from neutral gas outside the ionized region or at the interface between these regions. The O I 63 μm line has been detected in NGC 7027 by Melnick et al. (1981). The flux they measure is substantially higher than expected on the basis of models, so the 63 μm line may be produced by a different process, possibly arising from the extensive neutral cloud known to surround NGC 7027. A recent spectrum of NGC 7027 taken by Bregman et al. (1981) identifies an emission peak at 6.62 μm with the ground-state transition of Ni II, probably also arising from gas outside the fully ionized region.

The ongoing development of high-resolution infrared spectrometers will inevitably lead to the measurement of other previously undetected lines. Lists of potentially observable lines can be found in Petrosian (1970), Olthof and Pottasch (1975), Simpson (1975), Garstang et al. (1978), and Watson and Storey (1980). These include the fine-structure lines of other p^2 ions, such as N II (at 122 and 204 μm); low-ionization species, such as CII (157 μm) and Fe II (5.34 μm); and ions of less abundant elements, such as Na, Ca, and P. Some of these lines are observable from ground-based telescopes; for example, the 11.8 μm line of Cl IV, searched for unsuccessfully in various H II regions, has only recently been detected in a planetary nebula (Roche 1982). Many of the lines lying in the far-infrared ($\lambda > 14$ μm) can be observed from the Kuiper Airborne Observatory (KAO). However, certain lines, e.g., Ne III 15.4 μm, have wavelengths that fall in terrestrial absorption bands that are opaque even at the altitude of the KAO. Observations of these lines will await the development of infrared spectroscopy from space platforms.

III. DIAGNOSTICS OF PHYSICAL CONDITIONS

Fine-structure lines of p^2 and p^4 ions, which have five levels in the ground configuration, offer a unique opportunity to probe the physical conditions in nebulae. The optical transitions yield sensitive indicators of the electron temperature T_e via the intensity ratios of transitions from the highest and second-highest energy levels (e.g., O III 4363 Å/5007 Å). The infrared lines, on the other hand, are insensitive to T_e, but sensitive to the electron density n_e. Different transitions within a triplet, such as O III 52 μm and 88 μm, generally have different critical densities and therefore their ratio is a good indicator of n_e. The combination of infrared and optical lines makes possible a simultaneous and independent determination of n_e and T_e in the O III zone, which comprises a large fraction of the gas in most planetary nebulae.

Measurements of the 88 μm O III line have been made for four planetary nebulae by this author, and the 52 μm line has been observed in two nebulae (Watson et al. 1981; Moseley 1982). Figure 2 demonstrates how such measurements can be combined with optical lines to derive n_e and T_e. The ratio I(5007)/I(88 μm) is used as a density indicator, and I(4363)/I(5007) yields the temperature. The grid lines indicate the

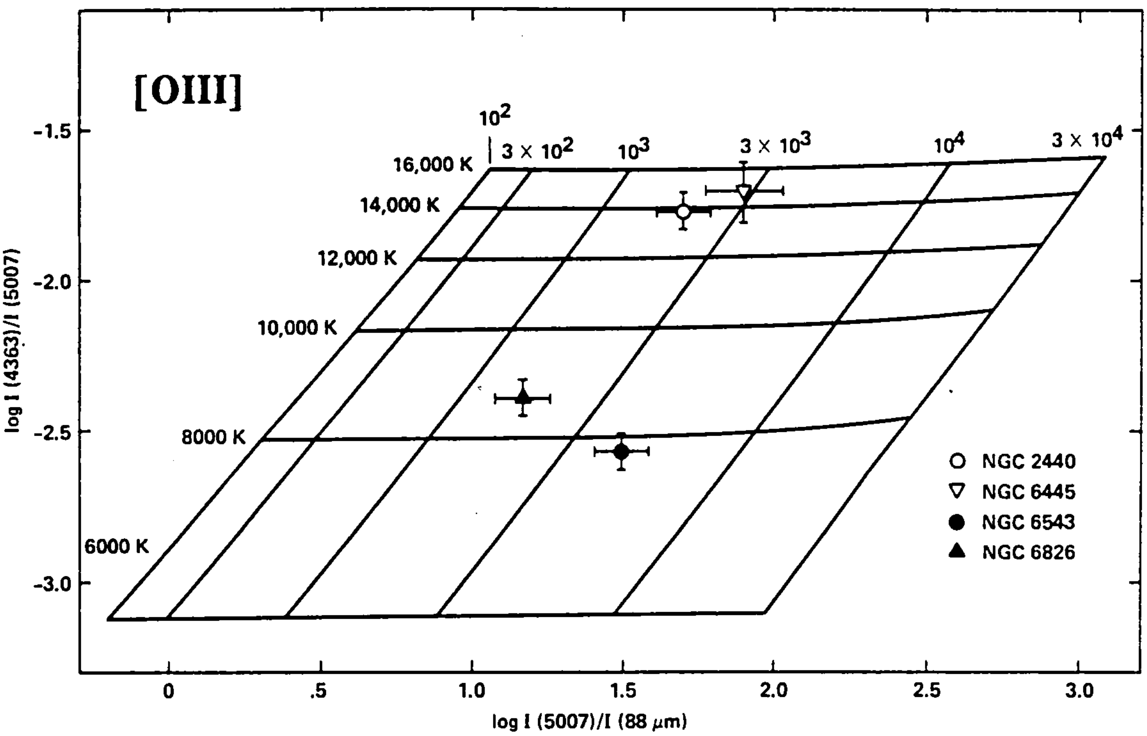

Figure 2. This figure demonstrates the use of observed line-intensity ratios of p^2 ions such as O III as diagnostics of the physical conditions. The vertical axis, 4363 Å/5007 Å, measures the electron temperature; the ratio 5007 Å/88 μm (horizontal axis) is a density indicator. The grid of intensity ratios was computed by solving the five-level equilibrium (see text).

loci of the line ratios for a variety of n_e and T_e values, from a five-level equilibrium solution. Lines of constant n_e and T_e are not orthogonal in this diagram because I(5007)/I(88 μm) is sensitive to temperature as well as density. The calculation assumed the transition probabilities of Garstang (1968) and the collision strengths of Eissner and Seaton (1974) for transitions between terms and the values of Saraph et al. (1969) for the fine-structure lines. The 88 μm line measurements in Figure 2 are fluxes measured by the author from the KAO using the spectrometer described by Storey et al. (1980) with a large beam, integrating over the nebula. Integrated 5007 Å fluxes were measured in the same beam (45") at Lick Observatory for NGC 6445, NGC 6543, and NGC 6826. The 4363 Å/5007 Å ratios for NGC 6543 and NGC 6826 are the large-beam (35") values of Bohuski et al. (1974). Fluxes of the optical lines for NGC 2440 are from Shields et al. (1981), and for NGC 6445, from Torres-Peimbert and Peimbert (1977). The O III densities derived for these objects are similar to values derived from O II in the same objects (Aller and Epps 1976). This result is important because it shows that these particular nebulae are quite homogeneous in their density structure.

The optical O III line emissivities depend strongly on the electron temperature, and the accuracy of ionic abundance determinations relative to hydrogen is mainly limited by the accuracy with which T_e is estimated. In addition, values of T_e determined from high-lying levels are weighted toward regions of highest T_e and highest line emissivity, so that ionic abundances will be underestimated if the effects of temperature variations within a nebula are neglected (Peimbert 1967; Rubin 1969). The magnitude of the variation in T_e is parameterized by the quantity t^2, the rms temperature fluctuation. Correction for this effect, using t^2 values derived empirically from line observations (e.g., Peimbert and Torres-Peimbert 1971), can lead to increases by a factor of about 2 in the derived ionic aboundances. The appropriate value of t^2 has been a matter of some controversy (Barker 1979). Probably the best way to detect the effects of a spread in T_e is to examine two temperature-sensitive line ratios of a single ion. For O III these could be I(4363)/I(5007) and I(5007)/I(88 μm), and the electron density n_e can be independently determined from the ratio I(52 μm)/I(88 μm). Thus, measurements of both infrared and optical lines would yield not only n_e and T_e, but also the magnitude of inhomogeneities in these quantities within the O III zone. Density fluctuations may also lead to an apparent positive value for t^2, but these effects are probably less important than those of temperature variations since the line ratios depend on a higher power of temperature than of density.

A similar analysis can be carried out for other p^2 ions such as Ar III and S III. The 18.7 μm S III line has been measured in several planetaries: NGC 7027 and BD+30°3639 (Greenberg et al. 1977), and NGC 6543 (McCarthy 1979). Combination of these observations with measurements of the $^1D-^3P$ lines near 9000 Å (Barker 1978b; Dinerstein 1980a,b) and of 6312 Å will yield n_e and T_e in the S III region, as was done above for O III. Other ions which could potentially be studied in this way include N II, Ne III, and Ar III, but these studies await the detection of infrared lines that have not yet been observed.

IV. ABUNDANCE DETERMINATIONS

As discussed above, infrared lines make it possible to observe ions that are difficult or impossible to measure in other spectral regions, and can therefore greatly improve abundance determinations for certain elements. Two of the best examples are Ne II and S IV, which have only been measured in the infrared. In the last few years, these lines have been measured sprectroscopically in a large number of planetary nebulae: Bregman (1978), Grasdalen (1979), Aitken et al. (1979), Dinerstein (1980a,b), and Beck et al. (1981).

The S IV ion in particular usually contains most of the sulfur in typical planetaries. Previous sulfur abundance determinations, even those making use of observations of S III as well as S II, showed systematic effects indicating that ionization correction formulae based on ionization potential coincidences with oxygen were not adequate (Barker 1978b, Pagel 1978). Measurement of accurate abundances for individual nebulae, and selection of the best empirical correction scheme (e.g., Natta et al. 1980) or of reliable models, requires direct measurements of the S IV ion. Table 2 presents results from the two infrared surveys in which total abundances were derived (Dinerstein 1980b and Beck et al. 1981). Average values for S/H are compared with values from Barker (1978b) based on the original ionization correction formula of Peimbert and Costero (1969), and with results from model-fitting reported by Aller (1978). Table 2 also compares Ne/H values from the infrared studies with values from Barker (1978a), Kaler (1978, 1980), and Aller (1978) for similar groups of nebulae. Most of the nebulae observed in the infrared lines so far have been relatively bright, compact objects belonging to a fairly young population (groups 1 and 2 of Peimbert 1978). Observations of a few high-velocity nebulae (previous references) show

TABLE 2

ABUNDANCES OF PLANETARY NEBULAE

	[S/H][a]	[Ne/H][a]	[Ar/H][a]
Infrared Studies			
Dinerstein (1980b)	7.02	8.11	---
Beck et al. (1981)	7.08	8.03	6.44
Optical Studies			
Barker (1978a,b)[b]	7.60	7.8	---
Kaler (1978, 1980)[c]	---	8.0	6.5
Aller (1978)	7.35	8.1	6.4

[a]Logarithmic abundance, $[X/H] = \log N(X)/N(H) + 12$.

[b]Values for intermediate population objects (Group II).

[c]Assumes $O/H = 4.5 \times 10^{-4}$, the value found by Kaler (1980) for intermediate disk population planetaries, and $Ne/O = 0.225$ (Kaler 1978).

no evidence of lower S/H in kinematically older nebulae, in contrast to the conclusion of Kaler (1980) that these nebulae have somewhat lower O/H. This question will be examined as part of an extensive study of S/H and Ne/H currently in progress (Dinerstein and Rank 1982).

Infrared observations can contribute even to measurements of such well-studied elements as oxygen. As discussed in Section III comparison of the infrared and optical O III lines will lead to better determinations of the electron temperature and its variations within a nebula. Through the dependence of the derived O^{++}/H^{+} abundances on the assumed values of T_e and t^2, this will yield more accurate abundance determinations. Observations of O IV will clarify the ionization equilibrium between O III and O IV and improve total abundance determinations in very highly ionized nebulae.

Another important p^1 ion, with an infrared transition at 57 μm, is N III. Most N/O determinations in nebulae are based on the optical N II/O II ratio (Kaler 1979); however, N III, like O III, is generally the most populous ion in planetaries. The ratio of N/O is particularly interesting because it can have an elevated value owing to processing within the star, and because planetaries are thought to be a significant source of nitrogen for enriching the interstellar medium. Recent UV observations (reviewed elsewhere in this volume) have led to better N/O determinations from N III and higher ions. Such determinations depend on the assumed extinction curve and electron temperatures. An alternative method is to use the infrared N III and O III lines, which are insensitive to T_e and sensitive to n_e, but from which the density can be measured, as discussed above. This approach has been applied to H II regions and can be used for some planetaries as well. Determination of N/O from N III/O III should make it possible to check the large overabundances of nitrogen derived for certain planetary nebulae.

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16. Abstract

Advances in infrared spectroscopy have led to the detection of many forbidden fine-structure emission lines in planetary nebulae. Measurements of these lines offer sensitive probes of the physical conditions and ionization structure, and lead to improved abundance determinations. This paper reviews recent observations and discusses the ways in which infrared line measurements can contribute to our knowledge of planetary nebulae.

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