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Phil. Trans. R. Soc. Lond. A 1969 **264**, 241-247
doi: 10.1098/rsta.1969.0019

III. NEBULAE AND EXTRAGALACTIC OBJECTS

Expected infrared spectra of gaseous nebulae

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If we are asked why we want to use the infrared to observe gaseous nebulae, we might reply with George Mallory, who was asked why he wanted to climb Mount Everest, 'Because its there'. More specifically, one reason is the very great space penetration possible in the infrared. Diffuse nebulae characteristically are close to the galactic plane, and interstellar extinction therefore prevents the observation of distant objects. At Hα the mean range to which diffuse nebulae can easily be observed is about 1500 parsecs (pc), while many of these nebulae are so reddened as to be nearly unobservable at Hβ. It is for this reason that at present the observation of diffuse nebulae is almost entirely limited to our own spiral arm and its immediate neighbours. However, because of the decrease of interstellar extinction to longer wavelengths, at 1 μm the range of observation would be about 3000 pc; at 2 μm about 10000 pc, comparable with the distance to the centre of the Galaxy; and at 10 μm, about 100000 pc, far larger than the diameter of the Galaxy. (The form of the interstellar reddening curve is from Whitford 1958.)

Another reason for observing gaseous nebulae in the infrared is that in this spectral region we have an opportunity of measuring lines from otherwise unobserved stages of ionization of common elements such as Ne^{+}, C^{+}, N^{2+}, etc. Yet another reason for wanting to observe in the infrared is that in this spectral region there are several pairs of lines which are collisionally de-excited at moderate densities and which therefore can be used to analyse the electron density. The specific transitions will be described later, but the infrared is favourable because the transition probabilities are typically smaller than in the visible regions (because of the ν^3 dependence), and de-excitation therefore typically occurs at relatively low densities in the range of interest in diffuse nebulae. Finally, in contrast to H II regions, H I regions are so cold that they emit essentially no visible or other 'high-energy' radiation, so the only chance of measuring them is in the infrared or radio-frequency regions.

Infrared observations of gaseous nebulae in the published literature seem to be entirely near-infrared observations made with the N photographic plates, or with S-1 photo-cathodes, out to just beyond 1 μm. They confirm that the typical nebular emission-line spectrum with a faint superimposed recombination continuum extends into the infrared. As an example, the measurements of relative line intensities in the central part of NGC 1976, the Orion Nebula, made with a photoelectric scanner by Aller & Liller (1959) are shown in table 1. The unit of intensity in table 1 can be normalized from absolute intensity measurements at Hα by Boyce (1966) and Gebel (unpublished), and is approximately 10 photons cm^{-2} s^{-1} received at the top of the Earth's atmosphere from a circle 1 min arc in diameter on the brightest part of NGC 1976, or 100 photons cm^{-2} s^{-1} from a circle

10 min of arc in diameter. NGC 1976 is the brightest diffuse nebula in the northern skies, but several small planetary nebulae have higher surface brightness. Similar infrared measurements by O'Dell (1963) and by Litter & Aller (1963) are available for about fifteen planetary nebulae, which in general tend to have a higher mean level of ionization than diffuse nebulae.

TABLE 1. OBSERVED INTENSITIES OF INFRARED LINES

NGG 1976. H II region. (Aller & Liller.)

0·6563	H I	Hα	350	0·9069	[S III]	$^3P_1$–$^1D_2$	72
0·6583	[N II]	$^3P_2$–$^1D_2$	55	0·9229	H I	$P9$	6
0·6716	[S II]	^4S–$^2D_{\frac{5}{2}}$	6	0·9532	[S III]	$^3P_2$–$^1D_2$	181
0·6730	[S II]	^4S–$^2D_{\frac{3}{2}}$	8	0·9546	H I	$P\epsilon$	8
0·7065	He I	2 ^3P–3 ^3S	13	1·0049	H I	$P\delta$	10
0·7136	[Ar III]	$^3P_2$–$^1D_2$	17	1·0830	He I	2 ^3S–2 ^3P	70
0·7319	[O II]	$^2D_{\frac{5}{2}}$–^2P	9	1·0938	H I	$P\gamma$	20
0·7330	[O II]	$^2D_{\frac{3}{2}}$–^2P	9				

The highest resolution infrared line profiles of gaseous nebulae are measurements of the He I 1·083 μm line in planetary nebulae by Vaughan (unpublished) at Mount Wilson Observatory. His observations were made with a Fabry–Pérot scanning interferometer working photoelectrically at the Cassegrain focus of the 60 in. telescope. The measurements were made with a resolution of about 4×10^4, and they show a complicated and asymmetric line profile. The 2 ^3S lower level of this line is highly metastable and planetary nebulae have large optical depths in it (Pottasch 1962), so the line profiles undoubtedly result from line scattering in the expanding nebulae.

The expected line spectra of gaseous nebulae in the infrared must be calculated on the basis of what we think we know of the physical conditions in these objects. Such calculations are of course intended only as a guide for the observationalist. Undoubtedly actual observations in the infrared will show some discrepancies with the calculations; these in fact will be new results and will give new information about the conditions within the nebulae. In the following calculations, it will be noticed that no concessions have been made to the Earth's atmosphere, the available detectors, etc., but a listing has been made of the strongest expected lines in the whole wavelength region from 1 to 1000 μm.

First we shall discuss the H lines, which in gaseous nebulae arise by recombination. The expected relative strengths are available from the calculations of Pengelly (1964), and are only very weakly dependent on temperature or density. The assumption that the nebula is optically thick in the Lyman lines (case B) is a good one in all nebulae that are bright enough to be observed. The calculated expected relative strengths of the H lines are listed in table 2. In this table, and in all the further tables in this paper, wavelengths are given in microns (μm) *in vacuo* (rather than in air as in table 1), and relative strengths are given in numbers of photons (rather than in energy units as in table 1), as these units are most appropriate for use over a wide range of wavelengths. By comparison with table 1, it can be seen that the unit of strength in table 2 is approximately 20 photons $cm^{-2}\,s^{-1}$ at the top of the Earth's atmosphere from a circle 1 min arc in diameter at the centre of NGC 1976.

The He lines in gaseous nebulae also arise chiefly by recombination, and are weaker than

Table 2. Expected infrared photon emission hydrogen lines

H II region. $T = 10000$ °K.

0·656	3–2	188	7·459	6–5	20
...	...	...	4·654	7–5	7·8
1·876	4–3	66	3·740	8–5	4·1
1·282	5–3	21	3·297	9–5	2·5
1·094	6–3	9·9	...	...	...
1·005	7–3	5·6	...	...	...
0·955	8–3	3·5	12·37	7–6	13
...	...	...	7·502	8–6	5·5
...	...	...	...	...	...
4·052	5–4	34	...	...	...
2·626	6–4	12	19·06	8–7	10
2·166	7–4	6·1	11·31	9–7	4·7
1·954	8–4	3·6	...	...	...
...	...	...	...	...	...

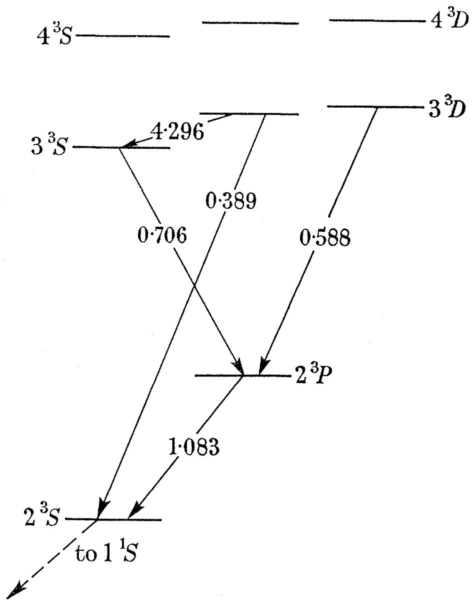

Figure 1

the H lines because of the lower abundance of He. The most interesting He I line is $2\,^3S$–$2\,^3P$, 1·083 μm, which as described above is scattered many times in escaping from a typical nebula. Because of the metastability of the $2\,^3S$ level, this line is also collisionally excited by thermal electrons. The energy level diagram in figure 1 shows some of the lower He I triplet levels. The optical depth in $2\,^3S$–$3\,^3P$, 0·389 μm also is significant, but much smaller than the optical depth in 1·083 μm, and there is observational evidence that 0·389 μm is appreciably weakened by absorption within the nebula and is partly converted into $3\,^3S$–$2\,^3P$, 0·706 μm (Pottasch 1962; Osterbrock 1964). In addition, the line $3\,^3S$–$3\,^3P$, 4·296 μm must be strengthened by this mechanism, though at present no observations of this line are available. The strongest singlet He I line is expected to be $2\,^1S$–$2\,^1P$, 2·059 μm, which should also be observed.

The characteristic spectral lines of diffuse nebulae are the collisionally excited lines or forbidden lines, known from the pioneering work of I. S. Bowen, D. H. Menzel, and others to be excited by collisions with thermal electrons. These lines are favoured in the infrared because the threshhold for excitation is low, and a list of those expected to be strongest is given in table 3. This list is intended to apply to diffuse nebulae, and we have

Table 3. Expected photon emission in collisional lines

H II Region. $T = 7500$ °K. Low-density limit.

0·7138	[Ar III]	$^3P_2$–$^1D_2$	6·8	18·7	[S III]	$^3P_1$–$^3P_2$	270
0·7321	[O II]	$^2D_{\frac{5}{2}}$–^2P	1·9	21·8	[Ar III]	$^3P_1$–$^3P_0$	22
0·7332	[O II]	$^2D_{\frac{3}{2}}$–^2P	1·6	33·6	[S III]	$^3P_0$–$^3P_1$	870
0·7753	[Ar III]	$^3P_1$–$^1D_2$	1·8	34·8	[Si II]	$^2P_{\frac{1}{2}}$–$^2P_{\frac{3}{2}}$	8100
0·9072	[S III]	$^3P_1$–$^1D_2$	4·1	36·1	[Ne III]	$^3P_1$–$^3P_0$	170
0·9535	[S III]	$^3P_2$–$^1D_2$	11	113	[O III]	$^3P_0$–$^3P_1$	5500
1·032	[S II]	^2D–^2P	2·0	122	[N II]	$^3P_1$–$^3P_2$	1700
6·983	[Ar II]	$^2P_{\frac{3}{2}}$–$^2P_{\frac{1}{2}}$	190	156	[C II]	$^2P_{\frac{1}{2}}$–$^2P_{\frac{3}{2}}$	23000
8·990	[Ar III]	$^3P_2$–$^3P_1$	100	174	[N III]	$^2P_{\frac{1}{2}}$–$^2P_{\frac{3}{2}}$	1000
12·8	[Ne II]	$^2P_{\frac{3}{2}}$–$^2P_{\frac{1}{2}}$	2700	204	[N II]	$^3P_0$–$^3P_1$	3900
15·4	[Ne III]	$^3P_2$–$^3P_1$	790	307	[O III]	$^3P_1$–$^3P_2$	4200

therefore assumed for the purpose of this calculation that each element is 80 % in the once-ionized stage and 20 % in the twice-ionized stage. The ten most abundant elements from the compilation of Aller (1961) have been taken into account. The collision strengths used are largely from the work of Seaton (1958), with a few others from Blaha (1964), Osterbrock (1966) and Delmar, Gould & Ramsay (in the press). For [Ar II], and for [Ar III] and [S III] ^3P–^1D, no calculated collision strengths are available and estimated values (Osterbrock 1966) were used. A temperature of 7500° has been assumed in the calculation of table 3, and the unit of intensity here corresponds to 50 photons cm^{-2} s^{-1} from a 1 min arc circle at the brightest part of NGC 1976. It can be seen that some of the strongest expected lines in the far infrared are [Ne II] 12·8 μm, [Si II] 34·8 μm, and [C II] 156 μm. In planetary nebula a similar emission-line spectrum but with a generally higher level of ionization, including some lines from higher ionization stages, may be expected.

The calculations summarized in table 3 were carried out in the low-density limit, in which every collisional excitation is followed by emission of a photon. However, at higher densities collisional de-excitation begins to become important, and the relative strengths of the lines change. For this reason it is possible to measure the electron density in a gaseous nebula by comparing the relative strengths of two lines of the same stage of ionization of the same element. This is the basis of the well-known λ 3727 [O II] method of measuring the electron densities (Seaton 1954; Seaton & Osterbrock 1957). Figure 2 shows calculated relative strengths of the two [N II] infrared lines, and shows that they provide a good means of measuring the density in the range 10^2 to 10^3 electrons/cm^3. At somewhat higher densities (about 5×10^3 cm^{-3}) the corresponding [O III] lines vary rapidly in relative strength, while at still higher densities (about 10^5 cm^{-3}) the [Ne III] lines can be used to measure the density.

Next we will turn our attention to H I regions, which are clouds of neutral interstellar material, shielded from ultraviolet ionizing radiation by the abundant H atoms. In these H I regions only elements with ionization potential less than that of H, i.e. C, Si, etc., are

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ionized. In H I regions the temperature is believed to average approximately 100°, though they are probably at least partly heated by collisions with other interstellar clouds, and then cool off by radiation. In H I regions only collisionally excited lines in the infrared can be expected to be observed, because of the high threshhold for transitions in the visible region. The infrared lines are mostly excited by collisions with the very abundant H atoms (Burgess, Field & Michie 1960). Table 4 gives a list of the strongest expected lines from

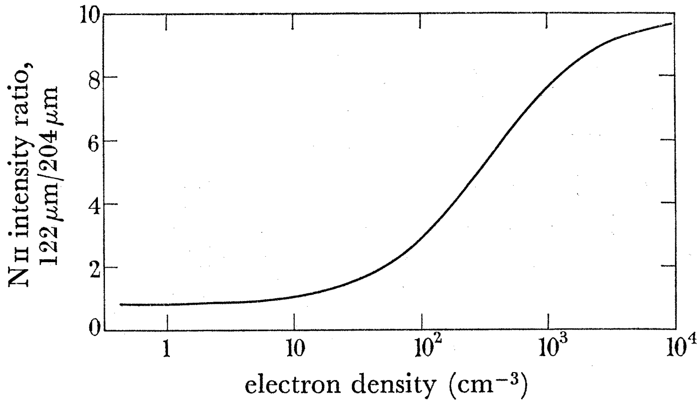

FIGURE 2

TABLE 4. EXPECTED INFRARED PHOTON EMISSION

H I region. T = 100 °K. 10% H_2

28·2	[H_2]	0–2	4·0	147	[O I]	$^3P_1$–$^3P_0$	4·9
34·8	[Si II]	$^2P_{\frac{1}{2}}$–$^2P_{\frac{3}{2}}$	0·4	156	[C II]	$^2P_{\frac{1}{2}}$–$^2P_{\frac{3}{2}}$	140
63·1	[O I]	$^3P_2$–$^3P_1$	31				

an H I region at T = 100°. The excitation cross-sections for the lines of the positive ions are taken from Dalgarno & Rudge (1964), the cross-sections for O I, from Smith (1966), and the cross-sections for H_2, from Takayanagi & Nishimura (1960). In this table the unit is about the same as the unit used for the expected H II spectrum listed in table 3, if we compare two clouds of the same size and density. It can be seen that the strongest lines expected from an H I region are about one-hundredth the strength of the strongest lines expected from an H II region, largely because of the lower temperature and lower degree of ionization in the H I region. H_2 molecules are expected to be present in H I regions, but their amount is quite unknown, and for the purpose of this calculation a relative abundance of 10 % H_2 molecules with respect to H has been assumed.

If an H I region is heated to, for example, T = 1000 °K by a cloud collision, then stronger infrared lines are expected. In fact at a temperature this high parahydrogen and orthohydrogen molecules are converted into one another fairly rapidly by exchange reactions with H, so both pH_2 and oH_2 should exist. Table 5 shows the expected infrared lines from an H I region at this assumed higher temperature.

If there are appreciable amounts of other interstellar molecules in H I regions, their lowest rotational lines should be observable in the far infrared, because they are easily excited in collisions with H atoms. The most abundant molecules after H_2 are probably

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Table 5. Expected infrared photon emission

H I region. T = 1000 °K. 10% H_2

8·05	[p H_2]	4–6	0·4	34·8	[Si II]	$^2P_{\frac{1}{2}}$–$^2P_{\frac{3}{2}}$	1·7
9·68	[o H_2]	3–5	18	63·1	[O I]	$^3P_2$–$^3P_1$	78
12·3	[p H_2]	2–4	30	147	[O I]	$^3P_1$–$^3P_0$	30
17·0	[o H_2]	1–3	97	156	[C II]	$^2P_{\frac{1}{2}}$–$^2P_{\frac{3}{2}}$	32
28·2	[p H_2]	0–3	4·2				

OH, CH and NH, or the ions OH^+, CH^+ and NH^+ all of which have strong allowed rotational transitions in the far infrared.

It may parenthetically be remarked that direct observation of H_2 to establish its presence in interstellar space is probably easiest in the near infrared. There is a resonance-fluorescence process, described by Gould & Harwit (1963), which occurs in H I regions near ultraviolet emitting stars—i.e. most strongly just outside H II regions. In this process H_2 molecules in the ground state absorb ultraviolet photons in the Lyman and Werner bands, and almost immediately emit a photon, returning in some cases to the $v = 1$ first excited vibrational level. From this level they then can return to the ground state by emitting infrared photons in the lowest few lines of the rotation-vibration band, particularly at the wavelengths listed in table 6 (Field, Somerville & Dressler 1966).

Table 6. Resonance-fluorescence lines of H_2

$v' = 1 \rightarrow v'' = 0$

J'	J''	λ	J'	J''	λ
0	2	2·627	2	0	2·223
			2	2	2·413
1	1	2·407	2	4	3·004
1	3	2·802			

Self absorption and stimulated emission are not completely negligible (Münch 1962), but their effects are expected to be small in typical H I and H II regions (density 10 to 100 particles/cm^3, diameter 3 to 10 pc). However, optical depths in the strongest lines of the order of τ_0 = 0·3 may occur, and therefore some of the lines listed in the above tables might perhaps be observed as absorption lines in bright infrared point sources such as the one in Orion described by Low.

This paper should close with the statement that although calculations such as it contains are instructive and perhaps useful in planning observational programs, real progress in the understanding of gaseous nebulae can only come from quantitative observational data.

I am most grateful to Dr R. J. Gould and Dr A. H. Vaughan for allowing me to quote their unpublished results, and to the National Science Foundation for support of the research on which this paper is based.

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