EMISSION LINE OBSERVATIONS OF H II REGIONS

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I. INTRODUCTION

Optical observations provide a wealth of information on atomic abundances, the excitation (level of ionization), the kinetic temperature, and the density of the gas in H II regions. However, obscuration by dust limits optical observations of galactic H II regions to those which are nearby (within a few kpc) and which are unobscured by the molecular clouds out of which they are formed (and so generally evolved). Radio observations are unhampered by extinction but provide much more limited information. The abundance of H^+, He^+ and occasionally C^+ can be determined as well as the kinetic temperature of the gas, but no direct information on the abundance of other species or the excitation is available.

Infrared observations are in several respects intermediate to optical and radio measurements. Extinction is typically small enough not to prevent observations completely, while large enough to have an important effect on measured fluxes. The infrared spectrum contains lines of several abundant ions, so that some information can be obtained about atomic abundances and relative ionic abundances, but only a few of these lines lie in portions of the spectrum which can be observed from the ground.

Because of extinction, infrared and radio observations are most important in studies of young, compact H II regions and of variations in abundances in the Galaxy. These types of studies will be emphasized in this review.

II. OBSERVATIONS

The various infrared emission lines and the sources in which they have been observed are listed in Table 1. The first five rows of this table give the species, wavelength, wave number, ionization potential range and deexcitation density for each line.

C. G. Wynn-Williams and D. P. Cruikshank (eds.), Infrared Astronomy, 237–245.

Table 1

Infrared Emission Line Observations of H II Regions

	He I	Bγ	Bα	Pfα	Ar II	Ar III	S IV	Ne II	S III	O III	N III	O I	O III	C II
λ(μm)	2.06	2.17	4.05	7.46	6.98	8.99	10.51	12.81	18.7	51.8	57.3	63.2	88.4	156.3
ν(cm^{-1})	4850	4616.5	2467.7	1340.5	1431.6	1112.22	951.43	780.42	534.39	192.99	174.39	158.	113.18	64.0
IP(eV)	24.6-54.4	13.6-	13.6-	13.6-	15.8-27.6	27.6-40.7	34.8-47.3	21.6-40.9	23.4-34.8	35.1-54.9	29.6-54.9	0-13.6	35.1-54.9	11.3-24.4
n_c(cm^{-3})					$6.0x10^5$	$3x10^5$	$7.1x10^4$	$3.6x10^5$	$3x10^4$	3000	800	104	300	30
W3			23		16,17	17,18,48	17,18,48	17,18,48	17,30				10,43	
M42						24	24	24	5,26,30	27,30		28,43	5,10,43	39
N2024									26					39
MonR2			23											
G298.2-0.3			38			38	38	38						
G333.6-0.2	54	54	38			38		1,4,11,38,51	13	32			32	
N6334										32				
N6357										32			10,32	
SgrB2													10	
SgrA		33				19,20		2,3,19,20,49,52,53	26	46			10	
M8										6			10	
W33					17	17	17	17	17					
M17									26,31	31,32	31,32	43	10,31,32,43,45	
G29.9-0.0					17	17,41		17,41	17					
W49									6	6			6,43	
G45.1+0.1			23		17	15,17	15,17	15,17						
W51	44	42,44	42						26	32	32		10,32,43	
S88		36	36			36	36	36						
K3-50	44	42,44	25,40,42			25	25	25						
G75.8+0.4			23,35		17	17,37	17,37	17,37	17					
S106			23					14,23						
DR21			40					40				43		
S156			23											
N7538		42	42		17	17	17	17,47	6,17	6			6,43	

Note: for references see end of paper

The remaining rows give references to observations of various H II regions.

III. PROBES OF NEBULAR CONDITIONS

A. Density

Infrared and radio observations provide means of determining both the rms density and the clumpiness of the ionized gas. The rms density is given by $n_{rms} = (EM/\ell)^{1/2}$ where the emission measure, $EM = \int n_e{}^2 d\ell$, can be determined from radio or infrared observations of the H II emission lines or free-free emission.

The density in the regions which dominate the line emission, or the clump density, can be determined from the ratio of two lines of a multiplet where one transition is more easily thermalized than the other. If $n_{c1} < n_e < n_{c2}$, transition 1 will be nearly thermalized with $I \underset{\sim}{\alpha} \int n_{ion}\, d\ell$, whereas transition 2 will depend on n_e and $I_2 \underset{\sim}{\alpha} \int n_{ion}\, n_e\, d\ell$. n_{c1} and n_{c2} are the densities at which the transitions are thermalized. Their ratio then measures the density in the regions dominating the line emission,

$$n_{clump} = \frac{\int n_{ion}\, n_e\, d\ell}{\int n_{ion}\, d\ell} \underset{\sim}{\alpha} \frac{I_2}{I_1}$$

The lines of S III (18,33 μm) and O III (52,88 μm) have been used to measure the density in the line emitting regions. Both of these line pairs have been observed by Moorwood et al. (1980a) and O III (52,88 μm) has been observed by Baluteau et al. (1980), Dain et al. (1978) and Melnick et al. (1978). The O III line ratio is most sensitive to densities $n_e = 10^3 - 10^4$ cm^{-3} and S III is most sensitive to $n_e = 10^4 - 10^5$ cm^{-3}. At low densities ($n_e < n_{c1}, n_{c2}$) the ratio depends only on the ratio of collision rates and at high densities ($n_e > n_{c1}, n_{c2}$) on the ratio of radiative decay rates. As Moorwood et al. point out, a lower value of n_e is derived from O III than S III because lower density regions dominate the O III emission. If, as in the case of O III in M17, both lines of a pair are deexcited at n_{rms}, the derived density can be smaller than n_{rms}. If only one line is deexcited, $n_{clump} > n_{rms}$. Moorwood et al. find that a three-component model can explain the observed line ratios in M17.

A mean density can be derived from lines such as O III (88 μm) and N III (57 μm) if n_e is large enough to completely thermalize the observed transition and if an assumption is made about the ionic abundance.

B. Excitation

The excitation, or level of ionization, of a region is best determined by comparison of lines of several ionization states of an element. O III (52 or 88 μm) and O IV (26 μm), S III (18 or 33 μm) and S IV (10.5 μm), and Ar II (7.0 μm) and Ar III (9.0 μm) can be used for this purpose. Herter et al. (1980b) have observed S III, S IV, Ar II, and Ar III in 6 HII regions, but use their fluxes primarily to study the elemental abundances (see below).

Because the lines of Ne II (12.8 μm), Ar III (9.0 μm), and S IV (10.5 μm) are observable from the ground, the ratios of their fluxes have been used to study the excitation of H II regions, assuming that the relative atomic abundances are solar. Lacy et al. (1979) use these three lines to show that the excitation of Sgr A is remarkably low. Similarly, Rank et al. (1978) derive excitation temperatures for G333.6 - 0.2 and G298.2 - 0.3, and Lacasse et al. (1980) discuss the excitation of W3.

C. Elemental Abundances

In a few cases, the observed ions are likely to represent a large fraction of their elemental abundances. S^{++} and S^{+3} are excited by photons of 23.4 - 47.3 eV, Ar^{+} and Ar^{++} by 15.8 - 40.7 eV and Ne^{+} by 21.6 - 40.9 eV. Reasonably accurate elemental abundances should be obtainable for T_* = 30 - 40,000K for S, 25 - 35,000K for Ar, and 30-35,000K for Ne.

Herter et al. (1980b) measure abundances of these three elements in six H II regions and find evidence of overabundance in G29.9 - 0.0, possible underabundance in W33, and near-solar abundances in the other sources. Lester (1979) and Lester et al. (1979a,b) find a possible overabundance of Ar in W3 and near-solar abundances elsewhere. They did not observe Ar^{+} or S^{++} in G29.9 - 0.0, but found Ne^{+} and Ar^{++} to have nearly solar abundances.

D. Motion and Distribution

If an emission line can be resolved, its lineshape can be used to study the dynamics of the ionized gas. The distribution in velocity and position of the line emission has been studied most extensively in Sgr A West by Lacy et al. (1979 and 1980a). They use the Ne II line to measure the mass distribution in the central parsec of the Galaxy. Beck et al. (1978 and 1979) measure the rotation curves in the central regions of M82 and NGC 253 with the Ne II line.

Lacasse et al. (1980) study the spatial distribution of fine-structure line radiation from W3 and find a distribution quite similar to the text-book description of an H II region; S^{+3} is concentrated toward an outer (He I, H II) shell. In contrast, Lacy et al. (1980b) find a more complicated, clumpy structure in many H II regions, with each clump containing all three ions.

E. Uncertainties

Although the extinction to galactic H II regions is not usually large enough to prevent infrared measurements, it can significantly affect the measured fluxes. Unfortunately, the infrared extinction curve is not well known, especially beyond 5 μm. Hydrogen recombination lines can be used to measure the extinction, but are available at only a few wavelengths. Lester and Rank (1980) have determined the 4 μm extinction to a number of H II regions, from the ratio of the Bα (4.0 μm) line flux to the radio free-free flux. Bγ (2.2 μm) and Pf α(7.5 μm) have also been observed and can be used in the same way. H 6α (12.3 μm), 7α (18 μm), and 7β (11.5 μm) are all quite weak, but would provide useful probes of the extinction if measured. The 10 μm silicate absorption has been determined by fitting the absorption of continuum radiation with an opacity law which fits the emission from the hot dust in the trapezium region. The underlying emission is assumed to be either a black body (model I) or a trapezium emission spectrum (model II) (Gillett et al., 1975). Unfortunately, we have no way of knowing the spectrum of the underlying emission. As a result, 10 μm extinction estimates are uncertain by a factor ~ 2. Lester and Rank (1980) show that $\tau_{4\ \mu m} \alpha\ \tau_{10\ \mu m}$, but the constant of proportionality depends on the underlying spectrum assumed to derive $\tau_{10\ \mu m}$. Uncertainties and simplifications in the models for nebulae also introduce substantial uncertainties in the derived nebular parameters. Absorption of ionizing radiation by dust, density inhomogeneities and charge exchange reactions can affect emission line fluxes and are not often included in models. The maps of Lacy et al. (1980b) demonstrate that many nebulae are quite clumpy. The effects of dust are discussed below.

IV. ABUNDANCE AND IONIZATION GRADIENTS

Gradients of the ionized helium abundance, y^+, and the electron temperature, T_e, in the Galaxy have been studied extensively at radio wavelengths. Churchwell et al. (1974) first noted a decrease in y^+ toward the galactic center and a correlation of the decrease of y^+ below cosmic y with the infrared excess over that attributable to absorption of Lyα radiation by dust. They conclude that both effects could be explained by selective absorption of helium-ionizing photons by dust. Churchwell and Walmsley (1975) found evidence for a decrease in T_e toward the galactic center which they attribute to increased cooling resulting from increased heavy elements in the ionized gas. Several subsequent studies (e.g. Mezger et al., 1980 and Wilson et al., 1979) confirm the gradients in both T_e and y^+, although individual objects show a large scatter about the mean trend.

Panagia and Smith (1978) show that the correlation of y^+ with the infrared excess can be explained by absorption by dust with a cross section ratio $\sigma(\lambda<504)/\sigma(504<\lambda<912) = \sigma_{He}/\sigma_H = 4 \pm 1$. However, Panagia (1980) concludes that the y^+ gradient can be explained by a gradient in the typical temperatures of the ionizing stars resulting from the effects of heavy elements in the stars. He also finds that the lowered stellar temperatures can explain the observed infrared excesses and in fact provide a better fit to the data than does selective absorption of helium ionizing photons.

Infrared emission line observations should be ideally suited to resolving these questions about abundances and excitation of distant H II regions. Herter et al. (1980b) have observed emission lines of He II, Ar II, Ar III, S III, and S IV from six galactic H II regions. They find an overabundance of all three elements in G29.9 - 0.0 at 5 kpc from the galactic center, as expected if an abundance gradient exists. However, W33 at 6 kpc appears to be underabundant. The primary uncertainties in this study are in the extinction correction, beam size corrections in comparisons of infrared and radio measurements, and the small size of the sample studied. As is discussed above, the extinction correction is likely to continue to be a serious problem.

No infrared survey looking for excitation gradients has yet been made. Sgr A West is ionized by radiation characterized by $T_{eff} \lesssim 31{,}000K$ (Lacy et al., 1980a), in agreement with the trend predicted by radio observations of y^+, but Sgr A may be a special case with some exotic source of ionizing radiation.

Lester (1979) and Lacasse et al. (1980) discuss the effect of dust on the relative abundances of the ions of Ne, S, and Ar. Lester uses [S IV] / [Ne II] as a measure of the excitation of the nebulae. He finds a correlation between [S IV] / [Ne II] and the free-free luminosities of H II regions, indicating that much of the variation in [S IV] / [Ne II] is due to the masses of the exciting stars. He also finds that model H II regions without dust fit the observed luminosity-excitation dependence better than do models with a λ^{-1} dust opacity in the ionizing ultraviolet.

Lacasse et al. (1980) study the fine-structure line emission from W3A. They conclude that the excitation of the nebula is lower than expected for a main-sequence star which produces the required ionizing flux. By including dust with $\sigma_{He} / \sigma_H = 5$, they were able to fit the observed ionization structure.

The differences between the conclusions of Lester and of Lacasse et al. appear to be due primarily to different interpretations of similar data. Both studies show a tendency for the required ionizing fluxes of the exciting stars of H II regions to be larger than expected for main-sequence stars of the required temperatures. This discrepancy could be due to the effects of dust, if σ_{He} / σ_H is large enough. Alternatively, it could be due to multiple ionizing stars, pre- or post- main sequence stars, or the effects of heavy element enrichment in ionizing stars. Detailed studies of the ionic distributions in nebulae combined with improved models may help resolve this question.

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DISCUSSION FOLLOWING PAPER DELIVERED BY J. H. LACY

T. L. WILSON: Mezger no longer appeals to "selective absorption" of He ionizing photons by dust. This change of attitude is due to the new stellar atmospheres of Kurucz (Astrophys. J. Suppl. 40, p.1, 1979).

LACY: Does he explain the variation in strength of the helium recombination lines within the Galaxy by these stellar models?

T. L. WILSON: Yes, this plus a variation in the relative abundance of oxygen, nitrogen, etc. The variation in the He to H ratio with distance from the Galactic Center is influenced by noise and systematic effects. These cause scatter in the trends (in addition to any intrinsic source-to-source scatter). The gradient in electron temperature is rather more securely established, however.

JOSEPH: In this context I would comment that S. A. Morris and I at Imperial College have shown that the notion of a "geometric effect" to account for variations in the He^+/H^+ radio recombination line intensity ratios is apparently inconsistent with the data itself, and that the proposed correlation between He^+/H^+ and IR excess has very little statistical significance.

T. L. WILSON: Measurements of radio recombination linewidths in W33 at Bonn (Bieging et al., Astron. Astrophys. 64, p. 341, 1979) show T_e must be less than 6000 K in this source. The claims of Herter et al. that heavy ions are underabundant in W33 are therefore surprising.

LACY: Herter et al. state that there are problems with their W33 data, so that the apparent overabundance may not be real.