INFRARED SPECTROSCOPY OF PROTOSTELLAR OBJECTS

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A. INTRODUCTION

The process of star formation occurs in regions of space not accessible to the traditional techniques of optical spectroscopy and photometry. Star formation begins with a density enhancement in a cold molecular cloud. Stellar gestation then occurs inside an obscuring cocoon of natal gas and dust, which for high mass stars may still be in place when the star reaches the Zero Age Main Sequence (ZAMS). During this time the new star gathers the material which will make up its total mass, solves its angular momentum problem, achieves hydrostatic equilibrium and is making the conversion from gravitational to nuclear energy. The only direct view of this remarkable process is by radio and infrared techniques. Unlike many areas of infrared astronomy, which are extensions of previous optical studies to other wavelengths, information about star formation is primarily gained through infrared and radio studies.

This review concentrates on the contributions of infrared spectroscopy to the subject of star formation. Several topics such as the extensive work done on the Orion Nebula, molecular hydrogen emission lines, dust emission, and evolved H II regions are covered in detail by other reviews in this book and will not be discussed extensively here. This review will concentrate on results rather than techniques as a review of techniques would need a separate chapter. The results have been obtained with filter wheel, grating, Fourier transform (FTS), and heterodyne spectrometers. When it is important the technique will be mentioned.

The structure of this review is divided according to physical processes rather than by wavelength region. There is, however, a general division of studies according to wavelength which is imposed by the nature of the star formation process. The early stages of star formation are generally accessible only by radio and far infrared spectroscopy due to the low excitation temperature of molecular clouds. Low excitation forbidden lines of neutral atoms and molecules such as

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CI and CO can be observed in these regions. The continuum shape of the emission can also be studied. More evolved stages can be studied at intermediate (5 - 30μm) infrared wavelengths. Dust and several unknown broad emission and absorption features appear at these wavelengths as well as moderate excitation forbidden lines. Near (1 - 5μm) spectroscopy is generally limited to the later stages of star formation. Recombination lines from surrounding H II regions or absorption lines against hot dust can be observed in this spectral region. All of these topics are discussed below. The limitations on space and time for this review necessitate that it be illustrative rather than comprehensive. No attempt has been made to include all work in the field but rather to give illustrative examples.

B. FORBIDDEN LINE OBSERVATIONS

The observation of forbidden lines is certainly not unique to the infrared spectral region; however, fine structure lines with very low excitation levels which may act as cooling lines in cool gas clouds can only be observed in the infrared. Lines detected to date include [CI] (610μm), [CII] (157μm), [OI] (63μm), [OIII] (51.8μm, 88.3μm), [NIII] (57μm),[SIII](18.71μm) as well as several lines at intermediate wavelengths such as [NeII] (12.8μ), [SIV] (10.51μm) and [ArIII] (8.99μm). The low excitation potential of these lines make them relatively insensitive to temperature in most regions (Simpson 1975) but they are sensitive to density.

The far infrared lines must be observed from airborne or balloon borne platforms in order to reduce the absorption due to telluric water vapor. Most of the current work has centered on the [OIII] 88.35μm line which has been observed in a large number of star formation regions (see references). This line has an excitation potential of 163^{o} K and is therefore easily collisionally excited. Of particular interest for cool clouds are the recent observations of the [CI] 610μm line by Phillips, Huggins, Kuiper and Miller (1980) with heterodyne techniques and the [CII] 157μm line by Russell, Melnick, Gull and Harwit (1980) with a cooled grating spectrometer. The 157μm [CII] line has an excitation potential of 92^{o} K and has been discussed as a prime coolant of gas clouds at low temperature (Dalgarno and McCray 1972, Jura 1978). A high luminosity was detected in this line from M42 (80 $L_{\odot}$) and NGC 2024 (50 $L_{\odot}$) although it does not appear to compete with dust in the energetics of either of these clouds. The CI line at 610μm was detected in 8 molecular clouds which are known to have associated H II regions. Phillips _et al_. (1980) found the spatial and velocity distribution of the CI emission to be similar to that of CO. The lower brightness temperature of CI in spite of an emission coefficient almost the same as CO (1-0) indicates that most of the carbon may be tied up in CO or dust.

C. CONTINUUM AND BROAD UNIDENTIFIED FEATURES

The usefulness of infrared spectroscopic studies is not necessarily limited to the detection of atomic or molecular lines. Accurate descriptions of the continuum flux are extremely valuable in constraining models for radiative transfer in the gas and dust around protostellar objects. Moderate resolution continuum spectra have also revealed broad absorption and emission features which are thought to be associated with water ice, silicates and other not yet identified materials.

Far infrared moderate resolution continuum spectra of several star formation regions have been obtained with FTS techniques from the NASA aircraft by Erickson, Pipher and others (see Bibliography). Of particular interest in these spectra are the deviations from single temperature blackbody curves. The emergent far infrared spectrum, which contains most of the power in protostellar objects, is dependent on the central source, the optical properties of the dust and ices in the source, and the geometrical temperature and density distribution of the material. It has not been possible, to date, to solve uniquely for each of these parameters but the available spectra indicate that there is a variation among sources and that optical depth effects play an important role.

Continuum spectra especially in the intermediate infrared and near infrared down to 3μm often show broad absorption or emission bands when studied at resolutions of ≈ 100 with filter wheel spectrometers. Some of these bands have reasonable identifications, such as the 9.7μm silicate feature and the 3.08μm ice band. Other bands at 3.3μm, 6.0μm, 6.8μm etc. are unidentified and may represent important diagnostic tools in determining the compositions and column density of the dust surrounding protostars. It is not yet certain whether these bands are due to solid or gaseous components. Recent work by Tokunaga and Young (1980) has shown that at a resolution of 3000 the 3.3μm emission band does not break up into resolved features. They rule out a gaseous absorption on these grounds and postulate a solid state resonance.

D. MOLECULAR ABSORPTION AND EMISSION LINES

Near infrared spectroscopy has been used to gain information about the surrounding medium as well as about the nature of the central protostellar object. The main source of molecular absorption lines in the near infrared is the system of vibration-rotation transitions of the CO molecule. The fundamental, first overtone and second overtone bands of CO occur at 5, 2.3 and 1.5μm respectively. Each band consists of a very large number of lines with lower levels which vary from the ground state to high excitation temperatures. The oscillator strengths for the individual lines decrease by a factor of 100 between the fundamental and the first and second overtone. The variation of oscillator strengths and excitation temperature make it possible to find unsaturated lines for observation.

Infrared absorption line studies complement the CO emission line studies in that the radio $^{12}C^{16}O$ lines are usually saturated and often observed at low angular resolution. Infrared lines on the other hand can be observed in non-saturated regions to monitor a narrow column determined by the angular extent of the infrared source. The infrared CO lines can provide both temperature and column density information if lines at several excitation temperatures are observed. In some cases it may be possible to gain information on the $^{12}C/^{13}C$ ratio in molecular clouds. This ratio is very important in determining total abundances from radio observations of the emission from the $^{13}C^{16}O$ molecule. The main work on CO absorption and emission lines has been carried out in the Orion region by Hall and his collaborators with a high resolution FTS. This work is described in detail by Scoville in this volume.

At present the most studied infrared molecular emission lines are those of molecular hydrogen. Molecular hydrogen is the most abundant molecule in the galaxy and has no radio transitions. A detailed account of the observations of molecular hydrogen is given by Beckwith in this volume. Very recently, however, the higher rotational transitions of CO have been observed in emission at far infrared wavelengths from the Kleinmann Low nebula by Watson, et al. 1980 and Storey et al. 1980. They have observed four lines of CO with upper J levels in the range between 21 and 30 at wavelengths near 100μm. The lines appear to be optically thin and tentatively seem to imply that most of the carbon is in the form of CO which is consistent with the CI observations discussed in Section B. These same workers also have a possible detection of the $\pi_{3/2}$ 5/2→3/2 doublet of the OH radical at 119μm. If the infrared CO lines are truly optically thin they should provide an important comparison with the radio CO lines. Unfortunately the levels observed may not be in LTE due to their high radiative transition probabilities.

E. RECOMBINATION LINE INFRARED SPECTRA

Interpretation of recombination line spectra is a well understood method of analysis which has been very successfully used in optical spectroscopy. The absolute strength of the hydrogen recombination lines is directly proportional to the value of Ne^2V in an H II region. The value of Ne^2V is in turn a direct measure of the Lyman continuum flux from the central object. Boundary conditions on the temperature of the central object can also be obtained by the ratio of hydrogen to He I and He II recombination lines.

The lack of optical flux from most protostellar objects limits the measurement of line fluxes to the infrared and radio regions. Information about the central objects is given by the total luminosity as well as the radio continuum or infrared line flux which give the proportion of the total luminosity which lies in the Lyman continuum if the lines are formed by recombination. If it is assumed that the central object is a ZAMS star then either the total luminosity or the ratio of Lyman to total luminosity uniquely fixes the spectral type of the central star. The radio and infrared measurements have different advantages and disadvantages. The radio measurements are not affected by extinction but are often subject to optical depth problems. The infrared lines, generally the Brackett series of hydrogen, are almost always optically thin but are subject to extinction. If both the radio and infrared flux is optically thin the ratio of the Brackett γ line at 2.16μm to the 5 GHz radio continuum is given by

$$f_{5\ \mathrm{GHz}} = 1.15 \times 10^{14}\ f_{B\gamma}\ \mathrm{Jy} \qquad (1)$$

where the Bγ flux is given in Watts m^{-2} (c.f. Wynn-Williams et al. 1978). The current detection limit on Bγ is about 10^{-17} watts m^{-2} which is equivalent to a radio flux of 1.15 mJy. If a 20 mag visual extinction is assumed then the minimum detectable infrared line is equivalent to a radio flux of about 6 mJy which is near the upper limits quoted for many radio studies. The two techniques are therefore roughly equal in sensitivity with the radio excelling for very high extinction and the infrared excelling for optically thick compact H II regions.

Several studies of the infrared recombination lines of hydrogen and helium have been carried out with filter wheel, grating and FTS techniques (e.g. Simon, Simon and Joyce 1979, Soifer, Russell and Merrill 1976, Thompson and Tokunaga 1979, and other references in the bibliography). Most of these studies have emphasized either the Bγ and Bα lines with some observations of the He I line at 2.0581μm and the 1.7 to 1.2μm region. A summary of these observations is given in Figure 1.

Figure 1 is a plot of the Ne^2V value for an object as derived from the Brackett line fluxes or radio measurements versus the luminosity derived from a combination of near, intermediate and far infrared photometry. The parameter Ne^2V has been used to unify the measurements under the assumption of free-free emission and Menzel's Case B recombination radiation. It is of course possible for other emission mechanisms to contribute to either the radio continuum or the infrared line flux. The plots for ZAMS stars and luminosity Class I stars from Panagia 1973 are also shown on the figure with the spectral classes marked at various points along the lines. The top legend indicates the percentage of the total luminosity that appears in Lyman continuum for ZAMS stars. The directions that errors in extinction, luminosity and distance will move the points is indicated on the figure. Most of the points on the figure were obtained from Bγ measurements (+). Sources in which only Bα was used are indicated with a (⊕). The point marked for BN assumes that the KL nebula is not powered by BN. If the KL luminosity is included the point will move up as indicated by the arrow. S140/IR, MonR2/IRS3 and GL2591 have upper limits on the line flux which are indicated by the arrows moving to the right. Both

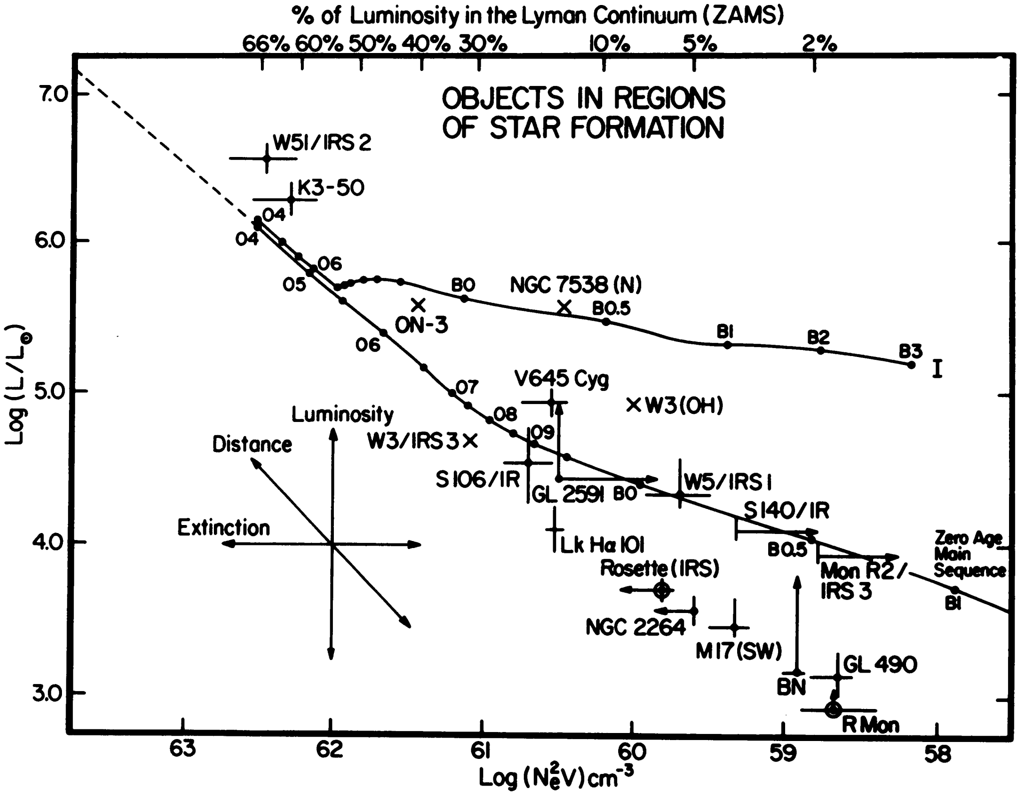

Figure 1. Plot of the Ne^2V value determined observationally versus the measured luminosity for several protostellar objects. See text for a detailed discussion.

S140/IR and MonR2/IRS3 are now thought to be multiple objects; therefore, their lack of Bγ flux is not surprising. A few radio sources from Thronson and Harper (1979) (×) have been plotted for comparison. The Bγ points listed for K3-50 and W51/IRS2 are in agreement with the radio values for those objects.

The basic conclusion to be drawn from Figure 1 is that the simple model of a ZAMS star surrounded by a dust free H II region inside a cocoon of dust does not fit most of the points in the figure. This conclusion is not new for the high luminosity objects but has not been observed before in intermediate luminosity objects. Details of this discrepancy are discussed in Section F.

F. EXCESS LINE FLUXES IN INTERMEDIATE LUMINOSITY OBJECTS

Most of the objects in Figure 1 do not fit the simple model of a ZAMS star surrounded by an H II region inside a dust cocoon. Stars with luminosities higher than 10^5 $L_\odot$ such as W51/IRS2 and K3-50 have line fluxes or Ne^2V values less than those expected for a ZAMS star of the same luminosity. This result has been well established by comparison of the radio emission to the observed far infrared flux (e.g. Jennings 1975). This effect is thought to be due to absorption of ionizing photons by dust inside the H II region. The infrared line studies are consistent with this hypothesis.

Objects with luminosities less than 5 x 10^4 $L_\odot$ show a trend opposite to the high luminosity objects. Many of the intermediate luminosity objects have line fluxes or Ne^2V values significantly in excess of the value expected from a ZAMS star of the same luminosity. It is interesting to note that most of the objects with excess line fluxes (as well as W5/IRS1 which has a normal line flux) have very compact H II regions with no measurable radio flux. Most of the objects also have no optical flux;therefore the effect is only observable at infrared wavelengths. Since these results are clearly in variance with the simple model either the observations do not imply the luminosity of Ne^2V values ascribed to them or a fundamental property of protostellar objects is being observed. Although the latter is far more exciting it is useful to consider the former first.

Figure 1 indicates the direction that points move in the diagram under the influence of various likely errors. Quantitative measures of line fluxes and hence Ne^2V must include a measurement of the extinction at the line wavelength. Extinctions are calculated from a combination of factors which include the relative strengths of the Brackett lines, the depth of the 9.7μm silicate feature, and photometric data at IR and visual wavelengths. Generally the smallest possible extinction value has been used to calculate the position of the objects in Figure 1. Even though it is important to measure the extinction as exactly as possible, it should be noted that most of the objects in Figure 1 would still appear to have excess line flux even if the Brackett line extinction was assumed to be zero. It is also possible that the observed infrared luminosity does not equal the total luminosity. This is possible if not all of the source photons are absorbed by dust and re-emitted within the beam width of the photometric observation. It is easy to imagine special geometries in which this may be the case. This special geometry argument, however, loses force in view of the large number of objects found to have excess line flux.

Errors in distance can also affect the conclusions about excess line flux. Distance errors scale both the luminosity and the line power by the square of the distance and are represented by 45° lines in Figure 1. At high luminosities the distance line is almost parallel to the ZAMS track. Most of the excess line flux objects would require distance errors of 4 to 5 to bring them back to the ZAMS. In some cases the lack of He I emission is then incompatible with the new ZAMS spectral type required at the higher distances. This review of observational problems indicates that the phenomenon is probably real and represents physical conditions present in the objects.

The excess line flux objects in Figure 1 occupy a region of the HR diagram which represents objects with radii 3 to 4 times smaller than their ZAMS counterparts with the equivalent Lyman continuum luminosity. This is not a state predicted by any current star formation theories or numerical simulations. An alternative is to abandon the concept of a single blackbody temperature for the star. The model would be a relatively low luminosity star at its normal ZAMS temperature with an added component of Lyman continuum luminosity to provide the ionized region for the emission lines. In view of the early evolutionary state of the objects it is natural to look at mass accretion processes as a possible source of energy for the excess Lyman continuum luminosity. It also appears that, whatever mechanism is responsible, it cannot compete with the high ionizing flux of stars with spectral types earlier than about O8 (Figure 1). This limitation is also consistent with mass accretion. Accretion luminosities are proportional to $M_\star/R_\star$ for a given accretion rate where $M_\star$ and $R_\star$ are the mass and radius of the central object. The ratio of M/R is essentially constant over the ZAMS when compared to the very large range of the Lyman continuum luminosity.

In order to be effective the bulk of the accretion luminosity must be emitted in the Lyman continuum. This suggests that the accretion energy is deposited in a small volume which results in a high temperature emission region. Two possible mechanisms are thin shock regions for spherically symmetric accretion and the boundary layer for impact on the star of material accreted from a disk. In all such cases a restriction on the emitted power is imposed by the Eddington limit. A simplified analysis for the boundary layer accretion from a viscous disk yields a limit on the accretion luminosity L_{AC} of

$$L_{AC} \leq 4/9 \; \frac{c\, G\, M_\star}{K_{av}} \;\approx\; 10^3 \; L_\odot \; M_\star/M_\odot \qquad (2)$$

where K_{av} is the average opacity per unit mass and is taken equal to the electron scattering opacity to determine the numerical factor on the right hand side. This limit is consistent with the observations of the phenomena only for stars later than about O8.

Emission processes other than recombination radiation should also be considered for the production of the infrared lines. The observed flux in the $B\gamma$ line is on the order of a solar luminosity for most of the objects which implies a total line luminosity of at least $10^3 \; L_\odot$ for either recombination or thermal line emission. This very high luminosity appears to be beyond the range of most chromospheric models.

The conclusion is that the line excess is the result of processes, probably accretion, occurring during the formation of the central star.

G. IR SPECTROSCOPIC SURVEYS

The increasing maturity and sensitivity of infrared spectroscopy has opened the possibility of comprehensive spectroscopic surveys of the infrared sources in star formation regions. Pioneering work in this area has been carried out by Elias (Elias 1978a, b, c) who has studied several dark clouds. Low resolution 2μm spectroscopy on most of the available objects was used to discriminate between field stars and objects associated with the cloud. The spectra also indicated the spectral type of several of the objects in the regions. No highly luminous O stars were found but the spectra were not of sufficient resolution to detect Bγ radiation from the H II regions around late O and early B stars. The infrared techniques allow much younger clouds with higher extinctions to be studied than can be handled in optical surveys. Complete surveys in both spatial extent and wavelength will allow both the energetics and evolution of star formation to be studied in dark clouds.

One of the difficulties in surveying the types of stars found in star formation regions is the lack of standard spectra by which the objects being studied can be identified. Later stars are easily identified by the strong CO absorption bands but relatively few criteria exist for stars earlier than K0. G stars have relatively few strong features but have weak hydrogen Brackett series lines and CO absorption. The Brackett lines increase in strength for F stars and the CO absorption disappears. The Brackett lines are significantly Stark broadened and tend to decrease in strength toward early B spectral types. O stars show almost no features in most cases; however, both early B and O stars show strong emission lines of hydrogen and helium if there is enough nearby material to produce an ionization bounded H II region. These characteristics have not been quantified, however, in the manner that optical spectral characteristics have been carried out such as K stars at 2μm (Ridgway 1974) and T Tauri stars at 10μm (Cohen 1980). The surveys will also be useful in determining the populations in the nuclei of other galaxies from infrared spectra as well as important in determining the nature of the objects studied.

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DISCUSSION FOLLOWING PAPER DELIVERED BY R. I. THOMPSON

WERNER: It is, of course, possible that energy is escaping in some of your objects, leading to an underestimate of luminosity. Also, since we may expect anisotropies in the distribution of matter around the source, I wonder if you have looked for effects such as correlations between luminosity deficit and reddening.

THOMPSON: The fact that 7 out of 8 objects show the effect described would argue against invoking special geometries. Most of these sources have no radio flux from them, and are therefore very compact regions which must have a rather high density around them. I would suspect that their dust has not yet blown away.

ZUCKERMAN: I think that you are somewhat underestimating the power of the VLA at 1 cm. Even right now your remarks are marginal, but as the receivers on the VLA improve, the radio sensitivity should become much better.

THOMPSON: That is true, but for self-absorbed sources, for instance those which Paul Harvey has found to be optically thick right to 100 μm, the infrared method will win, while for less compact objects radio observations will be more sensitive.

SANDELL: Can you detect sources in Brackett-γ or -α which cannot be detected photometrically?

THOMPSON: No. If they cannot be seen broadband they cannot be seen narrow band.