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THE STRUCTURE OF CIRCUMSTELLAR SHELLS
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Final Technical Report

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1 Introduction

This document provides a report on research activities carried out with the support of NASA grant NAG 5-1174, **The Structure of Circumstellar Shells**, funded under the Astrophysics Data Program. The research carried out with the support of the grant is a study of the properties of circumstellar dust shells for which spectra are available through IRAS low resolution spectrometry. The research consisted of the development and application of models of axisymmetric circumstellar shells and a preliminary survey of the applicability of neural nets for analysis of the IRAS LRS spectra of circumstellar dust shells.

2 Axisymmetric Dust Shell Models

To study the properties of axisymmetric circumstellar dust shells, I worked with former graduate student Alan Collison to develop a model for the radiative transfer in axisymmetric dust distributions. We used the model to calculate spectra and maps of the distribution of thermal and scattered radiation as observed from a variety of inclinations at many wavelengths (Collison and Fix 1990).

The dust shell models described in Collison and Fix (1990) consist of a central star surrounded by dust particles which are confined to the region between an inner radius and an outer radius. The inner radius corresponds to the point at which material ejected from the mass-losing star cools to the point that dust condensation occurs. The outer radius is chosen so that there would be no significant dust absorption, emission, or scattering at larger distances if more distant dust were included in the calculation. We used a ratio of outer to inner radius of 100.

The dust is assumed to have a density distribution which depends only on radius and polar angle. That is $\rho = \rho(r, \Theta)$. Although azimuthal angle does not appear explicitly in the equations, this is still a three-dimensional radiative transfer problem. We also assume symmetry with respect to the equatorial plane of the dust shell. At each point in the shell, a direction is specified by the angles θ and ϕ, where θ is measured from the outward radial direction and ϕ is measured with respect to a plane containing the radius vector and the polar axis of the dust distribution. The shell is divided logarithmically into radial divisions and into angular divisions.

A complete description of the circumstellar shell consists of specifying the radiation field $I_\lambda(r, \Theta, \theta, \phi)$ and the dust temperature $T(r, \Theta)$ at each grid point in the shell. These quantities are determined by solving the equation of radiative transfer

$$\omega \cdot \nabla I_\lambda = -k_\lambda \rho (I_\lambda - S_\lambda)$$

where I_λ is the specific monochromatic intensity in the direction ω, S_λ is source function, and k_λ is the total extinction coefficient. We assumed isotropic scattering and local thermodynamic equilibrium, in which case the source function is given by

$$S_\lambda = \frac{\kappa_\lambda}{k_\lambda} B_\lambda[T(r, \Theta)] + \frac{\sigma_\lambda}{k_\lambda} J_\lambda(r, \Theta)$$

where B_λ is the Planck function, κ_λ is the mass-absorption coefficient, σ_λ is the scattering coefficient, and J_λ is the mean intensity. We assume that the net energy transfer through the shell is dominated by the radiative flux so that radiative equilibrium holds and

$$\int \kappa_\lambda J_\lambda d\lambda = \int \kappa_\lambda B_\lambda(T) d\lambda.$$

We seek the shell temperature structure which is consistent with the assumption of radiative equilibrium.

To our knowledge, for the geometry we consider and for a general opacity spectrum, no closed-form solution to the radiative transfer problem has been obtained. To solve the problem, we used an integral form of the transfer problem and an iterative scheme to find the self-consistent solution which satisfies radiative equilibrium and the assumption that the luminosity of the shell plus star is the same for all radiative distances.

In our iterative scheme, we choose values of the temperature and mean intensity throughout the shell. From these, we compute the source function, from which the intensity distribution can be calculated using the equation of radiative transfer. New values of the mean intensity and temperature can then be computed from the intensity and radiative equilibrium. In general, the new temperatures and mean intensities will not be the same as the initial guesses. Thus, new guesses for these quantities must be made and the process repeated until consistency is achieved and total luminosity is conserved in the shell. We found that simply replacing the old guesses by the computed quantities does not result in a converged solution. In order to obtain appropriately updated values of mean intensity and temperature, we use a generalization of a scheme used by Pollack and Ohring for a study of planetary atmospheres.

2.1 The Models

In our models, we chose 3000 K as the temperature of the central star and 1000 K as the temperature of the inner radius of the dust shell. For the optical properties of the circumstellar particles, we used the results of Draine, who tabulated the complex dielectric function of "astronomical silicate". We assumed the particles scatter isotropically and have a radius of 0.1 μm. We used two separate dust density distribution. One of these is a "doughnut" like distribution and the other a flattened, "disklike" distribution. In both cases, the radial distribution of the dust (for a given value of Θ) was assumed to fall as r^{-2}. This distribution corresponds to the radial density profile for a constant velocity wind. The ratio of polar optical thickness to equatorial optical thickness ranged from $\frac{1}{2}$ to $\frac{1}{8}$.

We found that the observed spectrum of a dust shell depended on the inclination of the viewing angle, particularly for thick shells with large ratios of equatorial to polar optical thickness. Figure 1 shows the spectra of three disk-like shell models viewed from above the pole and above the equator. The model for an optically thick shell with an optical thickness ratio of 8 shows an

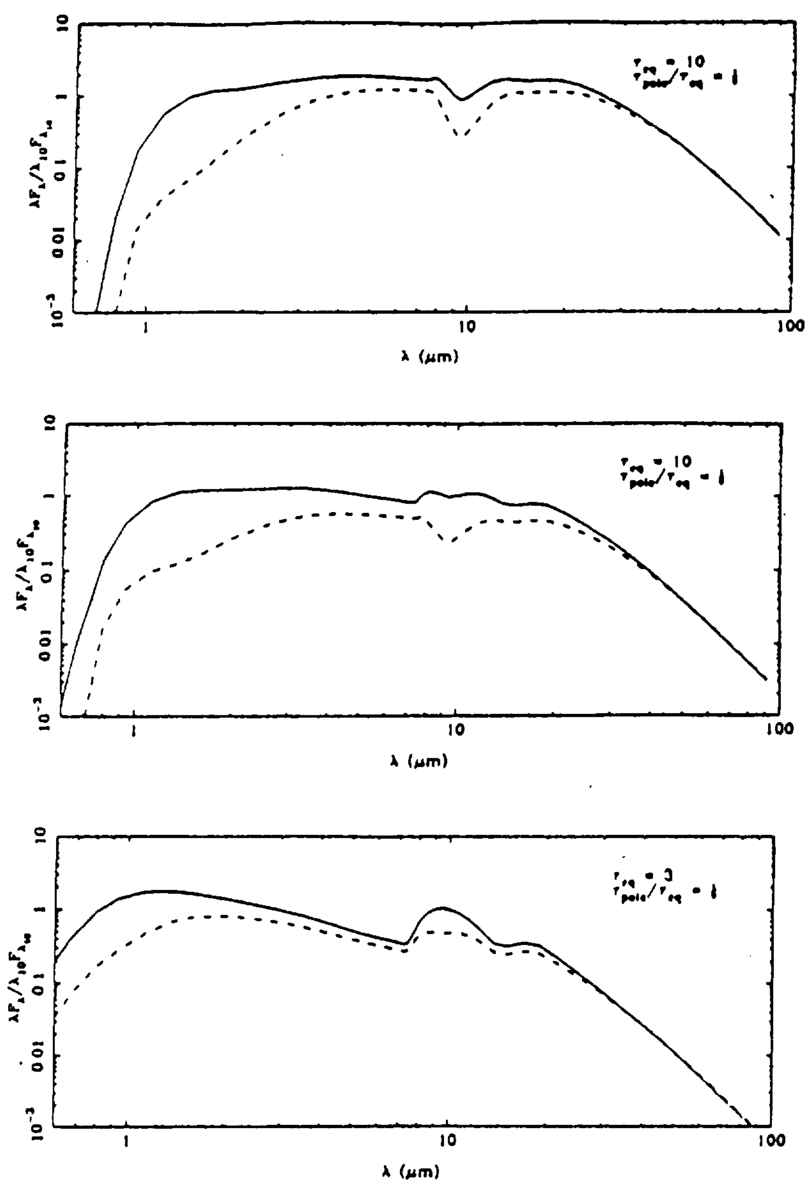

Figure 1: Energy distributions for three disk-like shell models. In each case the spectrum seen from above the pole is given by the solid line, the spectrum seen from above the equator is given by the dashed line. The top figure is for a shell with a 10 μm equatorial optical thickness of ten and a ratio of equatorial to polar optical thickness of two. For the middle figure, these parameters are ten and eight and for the bottom figure, three and eight.

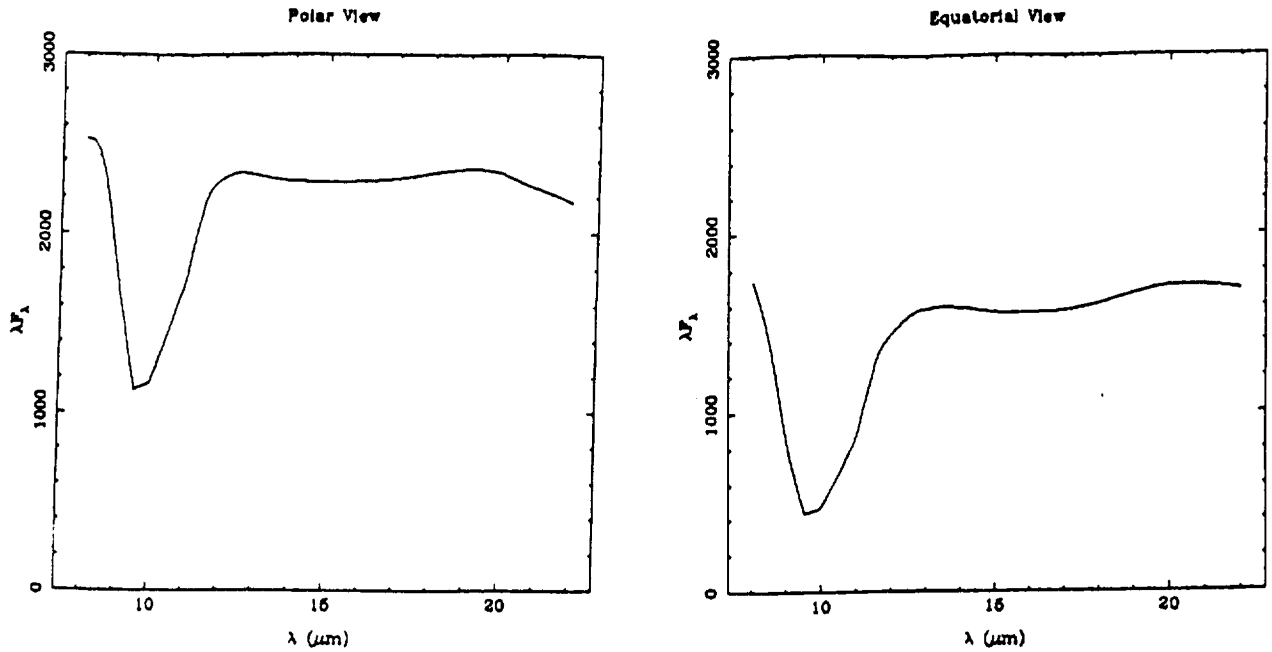

Figure 2: Spectra for an axisymmetric circumstellar dust shell as seen from above the pole and above the equator.

especially dramatic difference between the polar and equatorial spectra. Seen from above the pole, the 10 μm region is in emission, from above the pole in absorption. The original models, however, lacked sufficient resolution in the 8 to 22 μm region to make a detailed comparison with measured LRS spectra.

As a next step, I used the axisymmetric circumstellar shell code which I developed with Alan Collison to examine the detailed appearance of the 8 to 22 μm region for different viewing angles. Figure 2 shows detailed spectra of the 8 to 22 μm region as seen from above the pole and above the equator of a shell in which the polar optical depth is 25% of the equatorial optical depth. The spectra are similar in the depth of their 18 μm features but very different in the depth of the 10 μm feature. The resemblance of the two model spectra shown in Figure 2 to the pair of observed IRAS LRS spectra in Figure 3 is encouraging. Comparison of the two pairs of spectra suggests that it may be possible to account for the range of similar, but not identical, LRS spectra as axially symmetric dust shells viewed from different angles.

3 Neural Nets

One of the most broadly influential scientific events in recent years has been the development of computer programs which attempt to simulate the learning and memorization which take place in

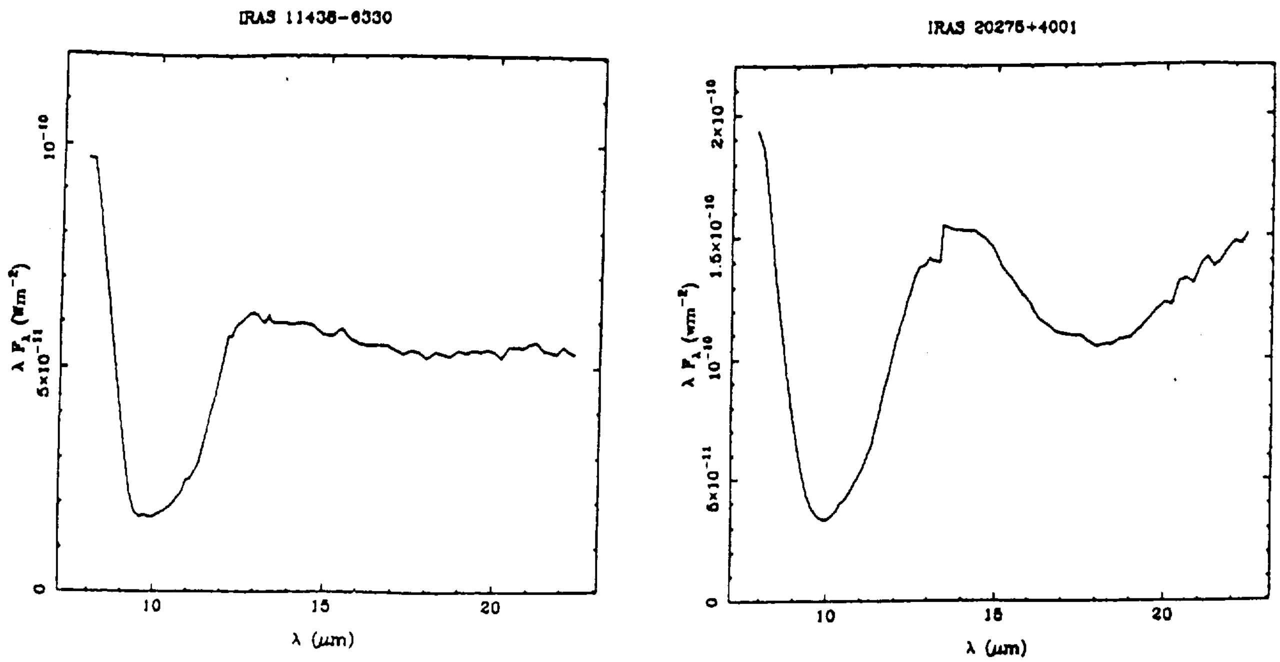

Figure 3: The 8 to 22 μm spectra of IRAS 11438-6330 and IRAS 20275+4001.

the human brain. These computer programs, or artificial neural networks (neural nets), model the brain as multiple layers of neurons which are connected to each other by a network of connections of variable strength As part of the work supported by the Astrophysics Data Program, I carried out a preliminary investigation of the usefulness of neural nets in classification and pattern recognition using the IRAS LRS spectra of circumstellar dust shells.

3.1 Pattern Recognition with Neural Nets

As a first experiment in the application of neural nets to the LRS data set, I trained a neural net to distinguish among LRS spectra with 10 μm emission features, those with 10 μm absorption features, and those which are featureless at 10 μm. The experiment used a three layer neural net which connected 81 input neurons to three output neurons. The input neurons were presented with the 81 values of normalized flux from an LRS spectrum. The desired output was (1,0,0) for an absorption spectrum, (0,1,0) for an emission spectrum, and (0,0,1) for a featureless spectrum. After hundreds of iterations, the net was able to classify all of the training spectra correctly as well as to correctly classify other LRS spectra, including many with relatively low signal to noise ratios.

In a second experiment, I trained a neural net to recognize the LRS classes which had been devised to describe silicate circumstellar dust shells with 10 μm absorptions. The classification scheme for IRAS LRS spectra was invented by the IRAS Science Team. For spectra showing silicate absorption, the scheme is based on the logarithmic depth of the 10 μm absorption. Class 31 spectra have weak 10 μm absorptions while the spectra in class 39 have such deep absorption features that there is almost no residual flux at 10 μm. I again used a neural net with two hidden layers and 81 input neurons. This time, however, there were four output neurons which, taken together, were interpreted as a binary code for the LRS class. That is, the matrices of connection strengths were trained so that a prototypical class 31 spectrum produced an output signal (0,0,0,1). A prototypical class 32 spectrum produced a (0,0,1,0) and so on through a class 39 spectrum and an output of (1,0,0,1). The training procedure used 20 exemplary spectra with very high signal to noise ratios. After training the net to correctly classify all 20 of the training spectra, I then used the trained net to classify other spectra. One result was the discovery that, according to the neural net, many of the spectra are misclassified. This occurs because the existing classification scheme separates spectra which have strong overall similarity but which differ somewhat near 10 μm. Another result was that the neural net found some spectra ambiguous and was unable to produce a simple classification in these cases. I believe that the difficulty that the neural net had in classifying "unknown" spectra reflects the one dimensional nature of the classification system devised by the IRAS Science Team. It is extremely difficult to find two circumstellar shells for which the LRS spectra are essentially identical. Spectra within the same LRS class may differ in the general slope of the spectrum, the depth of the feature at 18 μm, and the shape of the 10 μm feature. The conventional IRAS classification system looks at a single spectral parameters. The neural net, on the other hand, is much more holistic in its comparison of one spectrum with another. Because it uses all of the available spectral information, it is also less susceptible to problems which arise when noisy spectra are classified. My experiments with neural nets and LRS spectra suggest that it may be possible to use neural nets to produce a classification system which groups spectra on the basis of the most general similarities in their appearance.

3.1.1 Development of the Classification System Using Neural Nets

I also experimented with using neural nets to develop a new classification system for the IRAS LRS spectra of circumstellar dust shells. The effort was motived by the desirability of a classification scheme based based on the entire 8 to 22 μm spectrum rather than simply the depth or height of the 10 μm silicate feature. Most of the efforts to train neural nets have used supervised learning, in which training examples with known classifications are presented. This assumes, obviously, that an adequate classification system already has been developed. In unsupervised learning, which is less well studied, the neural net must develop its own criteria for class membership. This is done by dividing the input vectors into groups on the basis of clustering.

The method I tried works by successive divisions of the ensemble of input vectors. This is done by correcting (iteratively) the connection strengths of a two layer neural net in order to maximize a criterion function, J, which is a measure of the mean squared distance of the input vectors from a trial hyperplane which divides the vectors into two groups. The connection strengths are corrected using a steepest-ascent algorithm until J reaches a maximum. The two resulting clusters of input vectors can each be divided until the division of a particular cluster results in a value of J which indicates that the cluster is homogeneous.

I tried this method on a small sample of the IRAS spectra of circumstellar shells. The twelve spectra used in the trial are shown in Figure 4. After only 100 iterations, a hyperplane was found that divided the spectra into two groups – those with emission and those with absorption at 10 μm. The criterion function, J, had a value of 0.986 and no point was closer than 0.982 to the dividing hyperplane. Thus, the division into the two groups was essentially perfect. Clearly, the method found that the most striking difference among the twelve spectra was the gross appearance of the 10 μm feature. A second division of the spectra with 10 μm absorption features resulted in a separation into two those spectra with deep absorption (LRS class > 35) and those with shallow absorption (LRS class < 35). The neural net divided the spectra with 10 μm emission features into those with LRS class 29 and those with other LRS classes. It appears that the discrimination was on the basis of the appearance of the 18 μm spectral region. With only twelve spectra in the sample, it wasn't possible to pursue further divisions to find out when the division had produced essentially homogeneous groups. The power of the neural net method of classification can be seen in the fact that the net did not need to be told which features of the spectra were to be considered and which were not. The divisions were carried out according to the extent to which one entire spectrum resembled another.

In the future it might be possible to develop and implement a classification of the entire set of IRAS LRS spectra of circumstellar shells. These spectra contain both obvious and subtle spectral features. I am uncertain about how difficult it would be to develop a classification system which can be applied to the entire range of circumstellar spectra. However, it seems possible that it would be necessary to to modify the technique in one of several ways. One possible modification is in the form of the criterion function to make it more (or less) sensitive to the distance of a vector from the hyperplane. It may also be necessary to abandon hyperplanes as decision boundaries in favor of curved decision boundaries using higher-order neurons.

The result would be a multi-dimensional classification system (rather than the one-dimensional system now in use) in which each class contains a relatively homogeneous collection of spectra. This should make it easier to understand the underlying factors which are responsible for the variety of LRS spectra of circumstellar shells. The relative importance of these factors, which include temperature structure, chemical composition, and stellar mass-loss rate, has been difficult to determine using the present, distinctly inhomogeneous classification system.

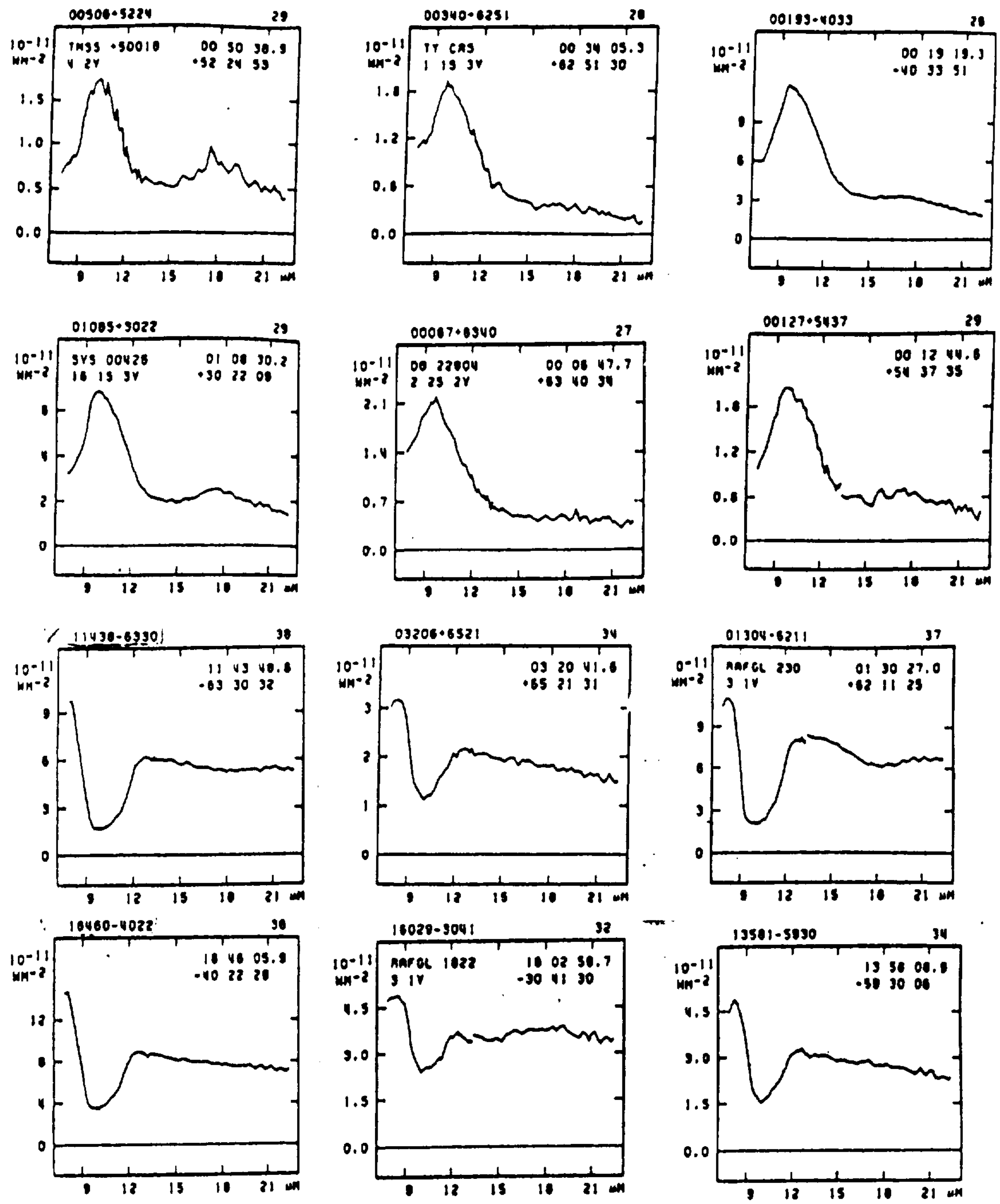

Figure 4: The twelve spectra used in the trial.

4 Publications Supported by the Grant

- Alan J. Collison and John D. Fix
  Axisymmetric Models of Circumstellar Dust Shells
  Ap. J. 368, 545-557, 1991.
- Alan J. Collison and John D. Fix
  1612 MHz OH Maser Emission from Axisymmetric Circumstellar Envelopes: Miras
  Ap. J. 390, 191-212, 1992.