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PRISM PROJECT OPTICAL INSTRUMENT

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INTRODUCTION

The scientific goal of the PRISM (Passively-cooled Reconnaissance of the InterStellar Medium) project is to map the emission of molecular hydrogen at 17.035 μm and 28.221 μm. Since the atmosphere is opaque at these infrared wavelengths, an orbiting telescope is being studied. My role has been to work on the optical design of the instrument.

The availability of infrared focal plane arrays enables infrared imaging spectroscopy at the molecular hydrogen wavelengths. The array proposed for PRISM is 128 pixels square, with a pixel size of 75 μm. In order to map the sky in a period of six months, and to resolve the nearer molecular clouds, each pixel must cover 0.5 arcminutes. This sets the focal length of the instrument at 51.6 cm. In order for the pixel size to be half the diameter of the central diffraction peak at 28 μm would require a telescope aperture of 24 cm; an aperture of 60 cm has been selected for the PRISM study for greater light gathering power. This sets the focal ratio at f/0.86.

In order to find the emission lines in the background continuum, and to allow for Doppler shifts of the lines at radial speeds on the order of several hundreds of kilometers per second requires spectral resolution of at least 3000. Thus it would appear that two imaging spectrometers are required, one for each line.

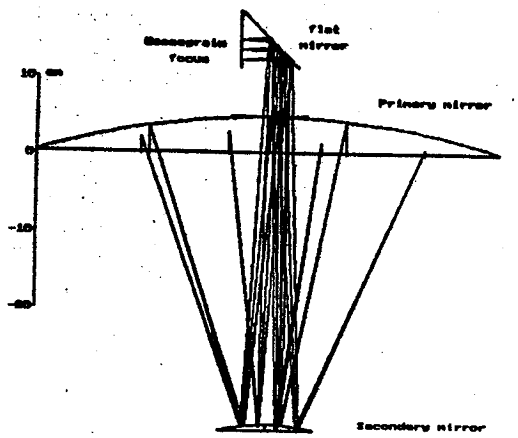
PRELIMINARY DESIGN

A 370 cm focal length Cassegrain telescope has been designed by John Jackson. A preliminary spectrometer design by Russell Chipman of the University of Alabama in Huntsville is based on a 360 cm focal length telescope followed by a prism monochromator and a grating spectrograph. The monochromator is used to select the two wavelengths of interest. The grating spectrograph is used in fifth order at 17 μm and third order at 28 μm. With this design, a single spectrometer can place both wavelengths of interest on a single focal plane array. The version of the spectrometer design I have seen does not yet give the correct scale on the array in the imaging direction.

My suggestion is that the instrument consist of the four stages listed below.

1. Cassegrain telescope. This stage gathers infrared radiation over a large aperture and forms an image of the sky at the Cassegrain focus.
2. Grating monochromator. The entrance slit selects a strip of the sky for spectroscopic analysis. The grating disperses light along the strip by wavelength, and the exit slits select two wavelength bands for further analysis.
3. Grating spectrograph. Light in each of the two bands is further dispersed by wavelength.
4. Final reimager. The spectrograph output is rescaled to fit on the very small focal plane array.

I have chosen a 284 cm focal length Cassegrain telescope in order to shorten the instrument for improved passive cooling. The telescope is shown in Fig. 1a, including a flat



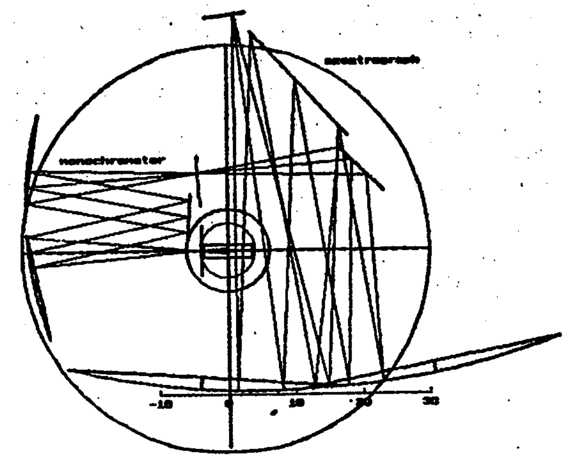


Figure 1a (left). 284 cm focal length Cassegrain telescope. 18 rays from three directions are shown. Figure. 1b (right). Grating monochromator and spectrograph. The 60-cm diameter circle is the outline of the primary mirror and the edge of the instrument volume. Three rays at 17 μm are shown.

mirror to redirect the light into the plane of the spectrometer. The distance between the primary and secondary mirrors is 40 cm, half the distance in Jackson's design.

I have chosen a grating monochromator because of the difficulty in finding a suitable prism material, and in order to avoid extreme curvature of the monochromator output slit.

A monochromator and spectrograph are shown in Fig. 1b. The four mirrors are paraboloids. The monochromator entrance slit is at the Cassegrain focus of the telescope. The monochromator grating is used in first order, and the two wavelengths are selected with two parallel exit slits. The spectrograph grating is used in fifth order at 17 μm and third order at 28 μm as in Chipman's design.

The design of the final reimager is yet to be completed. The optical parameters of the design are listed in Table 1.

PERFORMANCE OF THE PRELIMINARY DESIGN

The diameters of the central diffraction peaks for a 60 cm circular aperture are 196 μm for 17 μm and 326 μm for 28 μm at the monochromator slits, and 36 μm and 59 μm on the array. Thus diffraction should not cause significant loss of light at the slits or blurring of the image.

Aberrations must be minimized at the monochromator entrance and exit slits and at the final focus. The telescope optics determine the aberrations at the entrance slit. Conic surfaces optimized only in shape lead to the spot diagrams of Fig. 2. The spots are near the required size of 0.0413 cm; the remaining aberrations could be reduced by further optimization.

Parameter	units	value
Effective focal length	cm	284.00
Primary mirror focal length	cm	49.36
Secondary mirror focal length	cm	-11.33
Primary/secondary separation distance	cm	40.00
Secondary/Cassegrain focus distance	cm	53.84
Primary mirror diameter	cm	60.00
Secondary mirror diameter	cm	12.12
Monochromator entrance slit width	μm	413
Monochromator collimator and reimager focal lengths	cm	25.00
Spectrograph collimator and reimager focal lengths	cm	55.00
Deviation by off-axis paraboloids	degrees	12
Monochromator grating groove density	mm^{-1}	9.5
Monochromator incidence angle	degrees	16.27
Monochromator diffraction angle, 17 μμ	degrees	-6.79
Monochromator diffraction angle, 28 μμ	degrees	-0.69
Spectrograph grating groove density	mm^{-1}	11.0
Mean spectrograph incidence angle	degrees	38.31
Mean spectrograph diffraction angle	degrees	18.31

Table 1. Instrumental parameters.

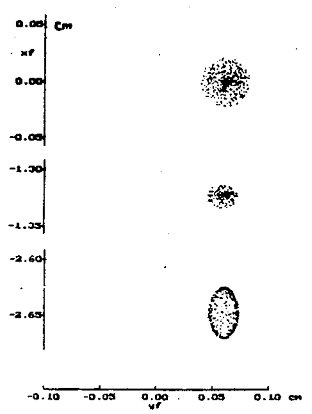


Figure 2. Spot diagrams at the Cassegrain focus/monochromator entrance. The center of the field is at the top and the edge of the field is at the bottom. Required spot diameter is 0.0413 cm.

The monochromator exit slit widths determine the widths of the spectral bands passed to the spectrograph. In order for each band to cover 32 pixels on the array, the widths are 0.043 cm for 17 μm and 0.071 cm for 28 μm. Spot diagrams at the monochromator exit slits are shown in Fig. 3a. The required spot sizes are not quite achieved, particularly at the edge of the field. The consequence is that if this design were used, there would be a loss of signal at the exit slits, in an amount which increases toward the edge of the image. There would <u>not</u> be significant blurring of the image, for the aberrations of the monochromator are compensated by the spectrograph.

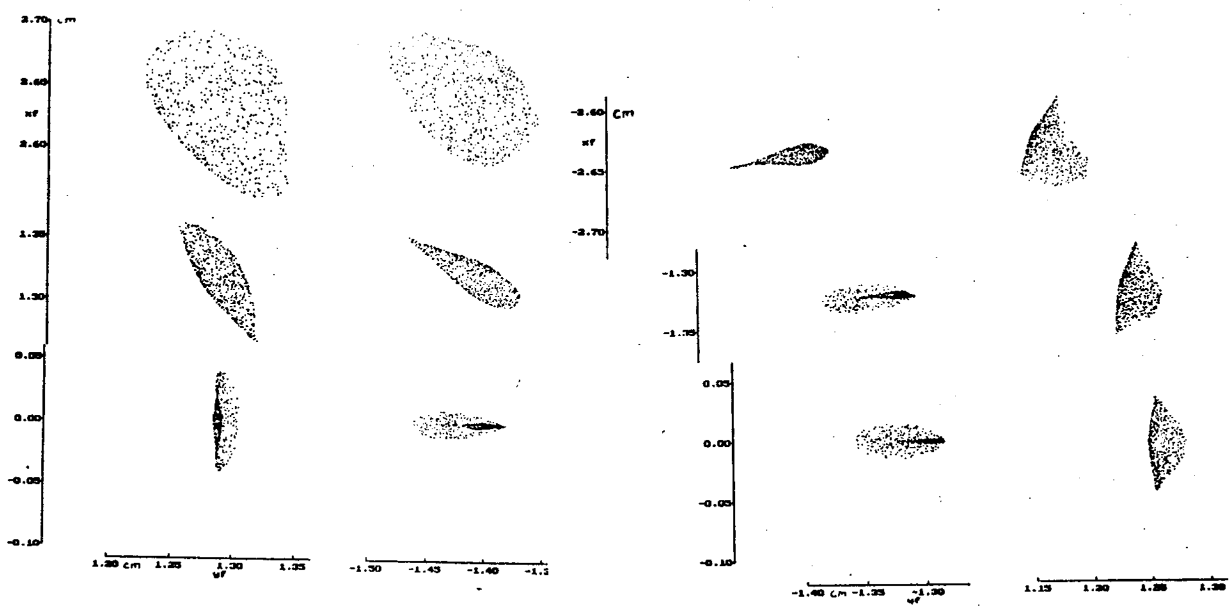


Figure 3a (left). Spot diagrams at the monochromator exit. The center of the field is at the bottom and the edge of the field is at the top. 17 μm is on the left and 28 μm is on the right. Required spot diameters are 0.043 cm for 17 μm and 0.071 cm for 28 μm. Figure 3b (right). Spot diagrams at the spectrograph output. Organized as in Fig. 3a. Required spot diameter is 0.0413 cm.

An acceptable final reimager has not been designed, but the spectrograph output has been analyzed. Spot diagrams are shown in Fig. 3b. The spots generally are within the required size of 0.0413 cm, so the reimager will only need to maintain the quality of the spectrograph output.

Three attempts to achieve the scale of the final image have so far not met with success. The first was to change the focal length in the monochromator or spectrograph by using different focal lengths for the off-axis paraboloidal mirrors. With this approach I was not able to reduce the aberrations to acceptable levels. The second effort was to design a reimaging lens or pair of lenses of the same materials, either CsI or KRS-5. With this effort I was not able to overcome the chromatic aberration between 17 μm and 28 μm. The third approach was to use a centered pair of mirrors, essentially a small Cassegrain telescope. So far I have not been able to reduce the aberrations to an acceptable level with components small enough to fit inside the instrument volume. Probably a third mirror, correcting plate, or meniscus lens is needed.

The throughput is limited primarily by the obstruction of the Cassegrain telescope and the efficiencies of the two gratings. My telescope design has only a 4.1 % obstruction by the secondary mirror. Grating efficiencies are limited to less than 91 % since 9% must go into secondary diffraction peaks between the principle peaks. Efficiencies must be calculated by electromagnetic theory, but I have made crude estimates based on scalar diffraction theory for the gratings in my design. The monochromator grating, if blazed at 5.7 degrees, should have efficiencies of about 70 % and 73 % for 17 μm and 28 μm, respectively. The spectrograph grating, if blazed at 52 degrees, should have efficiencies of about 46 % and 70 % respectively. Allowing for 99 % efficiency at each of 8 mirrors, the efficiencies of my design are about 28 % and 45 % for 17 μm and 28 μm, respectively.

The efficiency estimates above do <u>not</u> take into account the losses at the monochromator exit slit implied by the spot diagrams of Fig. 3a. There will also be losses in the final reimager, and reflection losses from the array. It should, however, be possible to antireflection coat the array[1] and any refractive surfaces in the final reimager, because of the coincidence noted by Chipman, that 5/4 of 17 μm is nearly equal to 3/4 of 28 μm.

In the spectrograph output, one-half arcminute on the sky is imaged onto 413 μm, and the entire field of 64 arcminutes is imaged onto a 5.3 cm line. The spectral lines are separated by a convenient distance of about 2.5 cm. The spectral lines are curved such that the top is displaced from the center by about 0.10 cm. The dispersion indicated by ray tracing is close to the amount I estimated for the design, so that after reimaging each pixel will cover 5.5 nm at 17 μm and 10.3 nm at 28 μm. The resolving powers are 3000 and 2700, respectively, and the velocity resolutions are 100 km/s and 111 km/s, respectively. I have not analyzed instrumental spectral linewidths.

The aberrations in the monochromator should be reduced. One way of doing this is to increase the focal lengths of the mirrors, but this will cause difficulties with packaging. Another approach is to improve upon the collimation and reimaging by using off-axis ellipsoids or other surfaces instead of paraboloids. My preliminary efforts indicate that ellipsoids can give improved collimation, but I have not yet incorporated them into the design.

The packaging of my design is very near to fitting within the instrument volume, which is a cylinder 60 cm in diameter and 20 cm tall. Fine tuning must be done to insure that components fit exactly within the allotted volume and that no rays intersect the wrong surfaces. The final reimager needs to be packaged as well.

The greatest problem is to reduce the spectrograph output to fit on the very small array. This problem would be alleviated if a larger array could be used.

REFERENCE

1. Rudisill, J. Earl and Hue Thi-Bach Nguyen, "Thin film coatings for improved IR detector performance", in <u>Infrared Thin Films</u>, Ric P. Shimshock, ed., pp. 141-55, 1992.