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A SEARCH FOR DIFFUSE BAND PROFILE VARIATIONS
IN THE ρ OPHIUCHI CLOUD

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PROFILE VARIATIONS IN THE RHO OPHIUCHI CLOUD
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ABSTRACT

High signal-to-noise profiles of the broad diffuse interstellar band at 4430 Å were obtained on the 2.2-m telescope at the Mauna Kea Observatory, using the newly-developed pulse-counting Multi-Anode Microchannel Array (MAMA) detector system. The purpose of the study was to determine whether the band profile varies with mean grain size as expected if the band is produced by absorbers embedded in grain lattices. The lack of profile variability over several lines of sight where independent evidence indicates that the mean grain size varies shows that $\lambda 4430$ is probably not formed by the same grains that are responsible for interstellar extinction at visible wavelengths. The possibility that this band is created by a population of very small (~ 100 Å) grains is still viable, as is the hypothesis that it has a molecular origin.

I. INTRODUCTION

One of the most interesting mysteries in astrophysics, and also one of the most persistent, is the identity of the absorbers that produce the diffuse interstellar bands. The fiftieth anniversary of their discovery (Merrill 1934) is approaching, yet fundamental questions remain, and while progress has been made, the solution is still elusive.

Historically, there have been two general classes of absorbers considered: molecular species, whose rotational energy level structure would provide a natural explanation for the breadth of some of the features; and absorption centers in solid grains, where matrix effects would cause the broadening. For years the former explanation was in disfavor, because it was thought that molecular species could not be sufficiently abundant, and furthermore, that the rotational structure should be detectable. Recently, however, the molecular hypothesis has returned to the arena, following the work of Danks and Lambert (1976), Douglas (1977), and Smith, Snow and York (1977), all of whom pointed out that, in light of new understandings of interstellar chemistry, the traditional arguments were invalid.

Meanwhile, the grain hypothesis became more complex, primarily as a result of ultraviolet extinction measurements, which, combined with scattering theory, led to the conclusion that there must be a broad range of grain sizes in the interstellar medium, either in the form of two (or possibly more) distinct populations (e.g. Witt 1973) or due to a very broad grain size distribution, as in the model of Mathis, Rumpl and Nordsieck (1977). Now the number of free parameters in the grains theory of diffuse band regions was greatly increased, as it became possible to resort to either the "large" grains (i.e. those with radii of order 0.5μ) thought to be responsible for visible-wavelength extinction and polarization, or to the very small grains (radii $\sim 100 \text{ \AA}$) thought to be responsible for the steep rise of extinction at far-ultraviolet wavelengths.

Correlation analyses, rarely definitive when working with interstellar quantities that all correlate in some way with overall column density, have failed to show clearly that the diffuse bands are more closely associated with one type of grain than with the other.

Theoretical considerations show that, if the bands are produced by absorption centers in the grains that are responsible for interstellar polarization, then there should be polarization structure within the band profiles. Intensive searches (Martin and Angel 1974; Fahlman and Walker 1975) have failed to detect any such structure [although this question is being re-examined by Wolstencroft (private communication)], so it appears that one class of grains has been ruled out as the diffuse band absorber. Traditionally, it has been assumed that the larger grains are the ones responsible for the visible-wavelength polarization, but Shapiro (1975) has argued that it may instead be the small ones, so it is difficult to be certain which class of grains is eliminated by the polarization measurements.

The present study undertakes a different approach. If the diffuse bands are produced by absorption centers in grain matrices, then under most circumstances the band profile will depend on the grain size and the density of absorbers within it (the basis for this is summarized by Smith, Snow and York 1977). The profile variations can be very marked, including substantial shifts of band central wavelengths and even the development of emission wings. Only in the case of very tiny grains, where the absorbers are not subject to lattice effects, but are instead essentially all exposed at the surface, would there be no significant profile dependence on grain size.

There are regions in space where grain size variations from one line of sight to another are strongly suspected. In view of the possibility that the diffuse band profiles might vary with grain size, it therefore becomes interesting

to search for profile differences between lines of sight where there are thought to be grain size differences. Previous studies (e.g. Savage 1975; Herbig 1975; Smith et al. 1981; Snell and Vanden Bout 1981), while not aimed specifically at this question, have failed to reveal any profile variability in several of the more narrow bands that could not be attributed to cloud velocity structure, so it seems improbable that these features (e.g. $\lambda\lambda 5780, 6196$) are produced in large grains. For the broader bands, however, where the grain absorber hypothesis is perhaps most tenable, it is much more difficult to obtain sufficient data quality, and previous data, while not revealing any clear-cut profile variations, have also not placed very stringent limits on such variations. The present paper, using data on the $\lambda 4430$ band obtained with a new electronic detector that eliminates most of the uncertainties of the older photographic spectra, is aimed at the question of line profile variability in a few lines of sight for which there is specific evidence of grain size differences.

The next section describes the observing equipment, including the detector; following that, Section III discusses the observations and the data reduction; results are given in Section IV; and their implications are discussed in Section V.

II. THE OBSERVING EQUIPMENT

A. The Telescope and the Site

The observations for this study were carried out on the 2.2-m telescope of the University of Hawaii at the Mauna Kea Observatory. This site was chosen in part because of its low latitude, providing easy access to the ρ Ophiuchi cloud, and in part because of the temporary availability, on the coudé spectrograph, of a superior detector system (the Multi-Anode Microchannel Array detector, described below) that has many desirable characteristics for the problem at hand.

The observations were carried out using the No. 3 camera of the Coudé spectrograph, providing a nominal reciprocal dispersion of 4.5 \AA mm^{-1} . This would normally have provided a spectral resolution of 0.24 \AA at 4000 \AA (assuming two pixels per resolution element), but due to a slight misalignment between the array detector and the focal plane during this initial observing run, the effective resolution (as determined from measurements of calibration lines) was degraded to 6 pixels (FWHM), or 0.72 \AA . This was more than adequate for observations of a feature whose FWHM is of order 20 \AA , and because the intent was to smooth the data over several pixels in any case, this misalignment caused no degradation of data quality for this program.

The spectrograph entrance slit width was set to match the measured spectral bandpass, so that the maximum throughput could be obtained. A slit width of 600μ was found to be the maximum allowable without further degrading the resolution, and this setting was used throughout. A slit width of 600μ corresponds to $1''.8$ on the sky, and the use of such a wide slit was definitely helpful under the moderate to poor seeing conditions.

B. The Detector

The Multi-Anode Microchannel Array (MAMA) detector, being developed at the Laboratory for Atmospheric and Space Physics of the University of Colorado, was used on the Coudé spectrograph to obtain the data analyzed in this study.

A detailed description of the MAMA detectors may be found in Timothy and Bybee (1981). Briefly, the components of a coincidence-anode visible-light MAMA detector system consist of a sealed tube assembly, containing an anode array and a single curved-channel microchannel plate (MCP) with the appropriate photocathode deposited on a mesh in proximity focus with the front face, together with the associated amplifiers, discriminators, and address-decoding and counting circuits. The spatial location of an event is determined by the simultaneous detection of a charge-pulse from the MCP by sets of two or more of the electrodes in the anode array which is mounted in proximity focus with the output face of the MCP, as shown schematically in Figure 1. The detector resolution elements (pixels) are defined by the dimensions of the anode electrodes. The photocathode material defines the spectral range of the detector while the MCP provides the high gain and narrow pulse-height distribution required for photon statistics, noise-limited operation. A charge-amplifier and discriminator circuit which issues a logic pulse for each output of the MCP that exceeds the pre-set threshold is connected to each set of the anode electrodes. Any valid combination of coincident logic pulses is decoded to determine the spatial location of an event and the number of events occurring at each location is stored in the corresponding word of a random access memory (RAM). This decoding and storage process is repeated at a rate determined by the pulse-pair resolution of the electronics. The (1×1024) -pixel MAMA detector used at Mauna Kea has a total of 32×32 pixels and, accordingly, requires a total of $32 + 32$ amplifier and discriminator circuits. The overall gain of the curved-channel MCP is about

10^6 at an applied potential of 1500 V. The microchannels have diameters of 12 microns on 15-micron centers and a very large number of microchannels are accordingly associated with each of the 6.5 mm x 25 micron pixels, giving excellent uniformity of response. On the No. 3 camera of the Coudé spectrograph the 1024 pixels provided a wavelength coverage of about 120 Å. The pulse-pair resolution of the electronics is 800 ns, providing 10% loss of detection efficiency at about 120,000 counts s^{-1} (Poissonian arrival) from the array. Since the MAMA detector is a random readout system, the total count rate can be distributed in any way across the array within the saturation limits of the curved-channel MCP (maximum rates $\sim 10^4$ counts s^{-1} pixel $^{-1}$ in this detector).

A number of different MAMA detectors have been developed, including several [such as (16 x 1024)-, (24 x 1024)-, and (256 x 1024)-pixel arrays] that are ideally suited for echelle spectroscopy, and these formats will soon be in use for ultraviolet rocket and balloon flight observations and visible-light ground-based studies.

The particular detector used in the present study has a bialkali photocathode, providing high sensitivity from the atmospheric cut-off longward to about 5000 Å (trialkali-photocathode detectors, sensitive to beyond 7000 Å, are also being fabricated, and within a few months spectroscopic observations will be underway with a detector equipped with such a photocathode).

Part of the process of preparing a MAMA detector for use includes an extensive "burn-in" period to remove alkali compounds from the microchannels following photocathode processing. The detection efficiency only reaches its full value after this process has been completed. The detector used in the present study was not fully burned in at the time of observations, and the detection efficiency (approximately 2-3% at 3000 Å) was only about one-fourth of the value that has since been attained in the laboratory through continued

operation. The low detection efficiency at the time of the observations resulted in count rates of $2-3 \text{ cts pixel}^{-1} \text{ s}^{-2}$ for a fifth-magnitude early-type star observed on the MKO 2.2-m telescope with the No. 3 camera in the Coudé spectrograph, under average seeing conditions. Thus, to achieve 1% photon statistics (per pixel, without summing over the number of pixels in a resolution element) required 3-5000 s of integration time for such a star.

A number of laboratory tests and a number of flat-field calibrations at Mauna Kea show that the detector is linear (up to count rates as high as $100 \text{ cts pixel}^{-1} \text{ s}^{-1}$) and truly photon-noise limited. No variations in the flat-field response to within the $\pm 1\%$ statistics were observed over the nine-night observing run. The dark counts were extremely low, amounting to less than $0.1 \text{ cts pixel s}^{-1}$ for the 1×1024 -pixel array for the detector tube used in the present study. This meant that it was possible (though none of the present data show it) to observe very faint, heavily-reddened stars, even at blue wavelengths.

III. THE OBSERVATIONS AND DATA ANALYSIS

As explained in Section I, the goal of the study was to compare diffuse band profiles in lines of sight where there was reason to suspect systematic differences in mean grain size. It was also desirable to minimize other variations from one line of sight to another, so that the principal effect, if any was seen, could be attributed to the grain size differences.

A well-studied region that appeared to fit this description is the cloud complex near the star ρ Ophiuchi. The ρ Oph cloud has been observed by a number of authors, and began to receive particularly intense attention following the work of Carrasco, Strom and Strom (1973), who, using both extinction and polarization data, demonstrated that within this cloud complex there probably are significant variations in grain size, with the largest grains in the deepest, presumably densest, regions. Later, Snow and Cohen (1974) showed that the strengths of the diffuse bands with respect to extinction diminish with depth in the cloud, consistent with the hypothesis that if the bands are created by grains, then the grains in the dense portions of the cloud may be modified in some way that makes them less efficient as band absorbers. Other research has supported the general idea that extensive gas-grain interaction has occurred in this cloud, which has low far-ultraviolet extinction (Bless and Savage 1973) and extreme gas-phase depletions in its densest regions (Snow and Jenkins 1980; Snow, Timothy and Seab 1982).

The observing program, therefore, consisted of measuring $\lambda 4430$ profiles for a number of lines of sight within the ρ Oph cloud, to determine whether any significant variations exist that could be attributed to differences in mean grain size from one line of sight to another. In addition, a few stars outside of the cloud were observed, to provide a control on the band profile in the lines of sight not dominated by dense clouds, and to provide spectra of

unreddened stars of comparable spectral type to the cloud stars, so that the effects of photospheric lines on the inferred $\lambda 4430$ profiles could be assessed.

Table 1 lists the stars observed. The time available was insufficient to cover all of the stars listed by Carrasco, Strom and Strom (1973), so an effort was made to select for a range of color excesses and grain size parameters (these and other ancillary data are included in the table).

For each star an exposure level of order $5000 \text{ cts pixel}^{-1}$ was reached, often by taking multiple exposures and subsequently summing them. The wavelength coverage was about 120 \AA , usually centered on $\sim 4435 \text{ \AA}$, the centering chosen so that the region around the band position was devoid of any particularly noisy pixels.

The wavelength scale was set by calibration-lamp exposures taken repeatedly throughout the night (although the system of spectrograph plus detector proved to be exceedingly stable, with no wavelength drifts of any kind), and flat-field exposures were obtained several times each night as well, so that the instrument response function could be divided out (again, the system was extremely stable, and it turned out that flat fields taken at different times, (even several weeks apart, were identical)). Backgrounds were assessed and removed according to numerous dark count exposures, also taken frequently throughout the night. Finally, the scattered light level was ascertained to be negligible (i.e. less than 5%) by comparison of standard star spectra with published spectral atlases (minor inaccuracies in the assumed scattered light level would have had no effect on the present study, anyway).

Following the addition of multiple exposures for each star, the summed spectra were then smoothed by 20 pixels (or 2.4 \AA) to reduce the remaining photon noise. For an exposure level of $5000 \text{ cts pixel}^{-1}$, this led to a net rms noise level (from one 2.4 \AA resolution element to the next) of 0.3%.

Where appropriate, the spectra of program stars were then divided by unreddened standard star spectra. This helped in pinpointing the wavelengths of photospheric features, although it did not fully remove them in most cases, because no effort was made to adjust the rotational line broadening of the standard stars to match that of the program stars. In principle, this could be done, but it was unnecessary for answering the general question towards which this study was directed.

There are several photospheric lines in the this region of the spectrum. The strongest of these are the He I lines at 4387.9 and 4471.6 Å, which bracket the diffuse band. Superimposed on the band itself are a number of weaker lines, most notably the O II doublet at 4417.9 Å. In the cooler star HD 183143, this section is occupied by the blend of Fe II λ 4416.9 and the 4419.6 Å line of Fe III. Other lines noticeably impinging on the diffuse band profile are Fe III at 4430.9 Å (most prominent in HD 183143), the λ 4437.6 line of He I, and the N II feature at 4447.0 Å.

IV. RESULTS

As a first step in assessing the data, the 4430 Å band in the spectrum of HD 183143, a particularly well-studied case, was compared with the profile obtained photographically by Herbig (1966). Figure 2 shows that the comparison is quite good. The most significant differences (such as the greater depths of the photospheric lines in Herbig's data) being attributable to differences in spectral resolution. The overall shape of the band is quite similar in these data obtained by widely disparate means. There are some minor differences in the slope of the red wing (which possibly could arise from minor errors in the rectification of the photographic data), but good agreement in quantities such as central depth and wavelength of greatest absorption.

Figure 3 shows the $\lambda 4430$ profiles for the program stars (including the reddened, non-cloud star HD 183143), arranged in order of increasing color excess. Continua have been drawn in, based on the flat continuum level in regions near the ends of the observed section of spectrum; i.e. some 50 Å to either side of band center. For all the program stars, present data presented clean, flat, and consistent continuum levels in these regions, so that little ambiguity was encountered. The choice of continuum level is critical for making measurements of band depths or assessing whether weak, broad emission wings may be present, but is not so important in determining whether the band central wavelength (or better yet, its deepest point) varies from one line of sight to another.

Figure 4 shows the $\lambda 4430$ profiles, renormalized and showing gaps where known photospheric lines obstruct the profile. In each case a vertical line indicates the point of maximum absorption depth.

Table 2 lists the band depths and wavelengths of maximum absorption. The full widths at half maximum and central wavelengths based on the half-depth points would also have been useful measures, but could not be accurately assessed in the program stars, nearly all of which have a photospheric line at about 4417 Å, obliterating the half-depth point in the short-wavelength side of the band profile.

A brief inspection of Figure 3 shows little or no significant variation in the band profile from star to star. A look at Table 2 confirms this, showing only minor fluctuations in the wavelength of maximum depth.

The figures give the general impression that the band is asymmetric, with an extended short-wavelength wing, although this is confused a bit by the photospheric line near 4417 Å. Such an asymmetry has been reported by other observers (e.g. Herbig, 1966; Bruck, Nandy, and Seddon 1969) and will be discussed in the next section.

V. DISCUSSION OF RESULTS

The present data appear to place strong constraints on the grain absorption center hypothesis for the origin of the $\lambda 4430$ diffuse band. The lack of profile variability strongly implies that, if grains are indeed responsible, it is not the grains that vary in size within the ρ Oph cloud, but must instead be some other grain population, one that is invariant throughout the observed portions of the cloud. Hence this study seems to eliminate the already-threatened "large" grains as the diffuse band carriers; i.e., those responsible for the visible-wavelength extinction, for it is these grain that appear to have grown to unusually large sizes in the ρ Oph cloud.

Most significant is the lack of any departure of the profile for ρ Oph itself from those of the other stars, because ρ Oph is the most deeply embedded cloud star of all those in this study. It stands out from the others in all measures of grain size, and has by far the greatest depletion of gas-phase elements. Whereas the differences among the other lines of sight are minor, and possibly might not produce profile variations in $\lambda 4430$, for the line of sight to ρ Oph the chances would be best that some dependence in grain size would show up. None does.

If some other grains are responsible for the 4430 \AA diffuse band, then the very small grains, known from UV extinction measures to be deficient in the ρ Oph cloud, may be the carriers. For sufficiently small grains, size variations would have little effect in the band profile. The depressed short-wavelength wing of the band may support this hypothesis, because it argues in favor of some kind of grain as the absorber. It was shown by Purcell and Shapiro (1977) that such a profile is expected under certain conditions, for absorption bands produced by impurity dipole absorption centers in small grains. Their model also predicts the presence of weak emission wings on the red side, which

do not appear in the present data, but this is highly dependent on the choice of continuum level. In general, the present data appear compatible with the Purcell and Shapiro grain impurity model. A depressed short-wavelength wing can, of course, also be produced by molecular rotational band structure, and by itself is not definitive.

The idea that the diffuse bands are produced by tiny grains is not a new one, having been discussed at length by Andriesse and de Vries (1981), for example. In view of the present result and the literature cited here, the small-grain hypothesis may be considered the most likely one at present, at least for the 4430 Å feature. Caution is urged, however, for even this proposed carrier has observational problems, the greatest of which is a lack of any strong correlation between $\lambda 4430$ absorption and far-UV extinction (Wu et al. 1981), something that might be expected if the same small particles are responsible for both, as suggested by Andriesse and de Vries (1981). Indeed, the best correlation between diffuse band and extinction found by York et al. (1981) was between band strength and infrared extinction! In view of the difficulties of obtaining accurate $\lambda 4430$ measures, however, it probably would be worthwhile to pursue the question of a possible correlation between $\lambda 4430$ and far-UV extinction, with high-quality data such as that obtained in the present study.

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TABLE 1. PROGRAM AND STANDARD STARS

STAR	HD	SPEC.	V	E(B-V)	E_{VL}/E_{BV} ^a	$\lambda_{\max}(\text{\AA})$ ^b	$-\log \delta(\text{Fe})$ ^c
PROGRAM STARS (ρ Oph cloud)							
δ Sco	143275	B 0.5 IV	2.33	0.16	2.71	--	1.99 - 2.13
β Sco	144217	B 0.5 V	2.63	0.20	2.56	6100	1.50 - 1.90
σ Sco	147165	B 1 III	2.9	0.40	3.54	5550	1.92 - 2.19
ρ Oph A	147933	B 2 IV	5.07	0.47	3.77	6900	2.35 - 2.75
STANDARD DIFFUSE BAND STAR							
	183143	B 7 I a	6.87	1.17			
STANDARD UNREDDENED STARS							
ζ Cen	121263	B 2.5 IV	2.54	-0.02	--	--	--
λ Sco	158926	B 1.5 IV	1.63	0.03	--	--	--

^aThe ratio E_{VL}/E_{BV} is a measure of the ratio of total to selective extinction, and is a grain size indicator. The data here are from Carrasco, Strom and Strom (1973).

^bThe parameter λ_{\max} is the wavelength of maximum extinction, and is also a grain size indicator, also taken from the compilations of Carrasco, Strom and Strom (1973).

^cThe logarithmic depletion of iron, relative to the solar abundance (with respect to hydrogen) is taken from Snow and Jenkins (1981).

TABLE 2. DIFFUSE BAND DATA ON THE OBSERVED STARS

Star	Central Depth (%)	Central Wavelength ^a (Å)	Equivalent Width ^b (Å)
δ Sco	3.1	4429.2 Å	0.8 Å
β ₁ Sco	3.4	4427.5 Å	1.3 Å
σ Sco	5.9	4428.4 Å	1.8 Å
ρ Oph	4.1	4428.0 Å	1.3 Å
HD 183143	16.7	4427.6 Å	3.5 Å

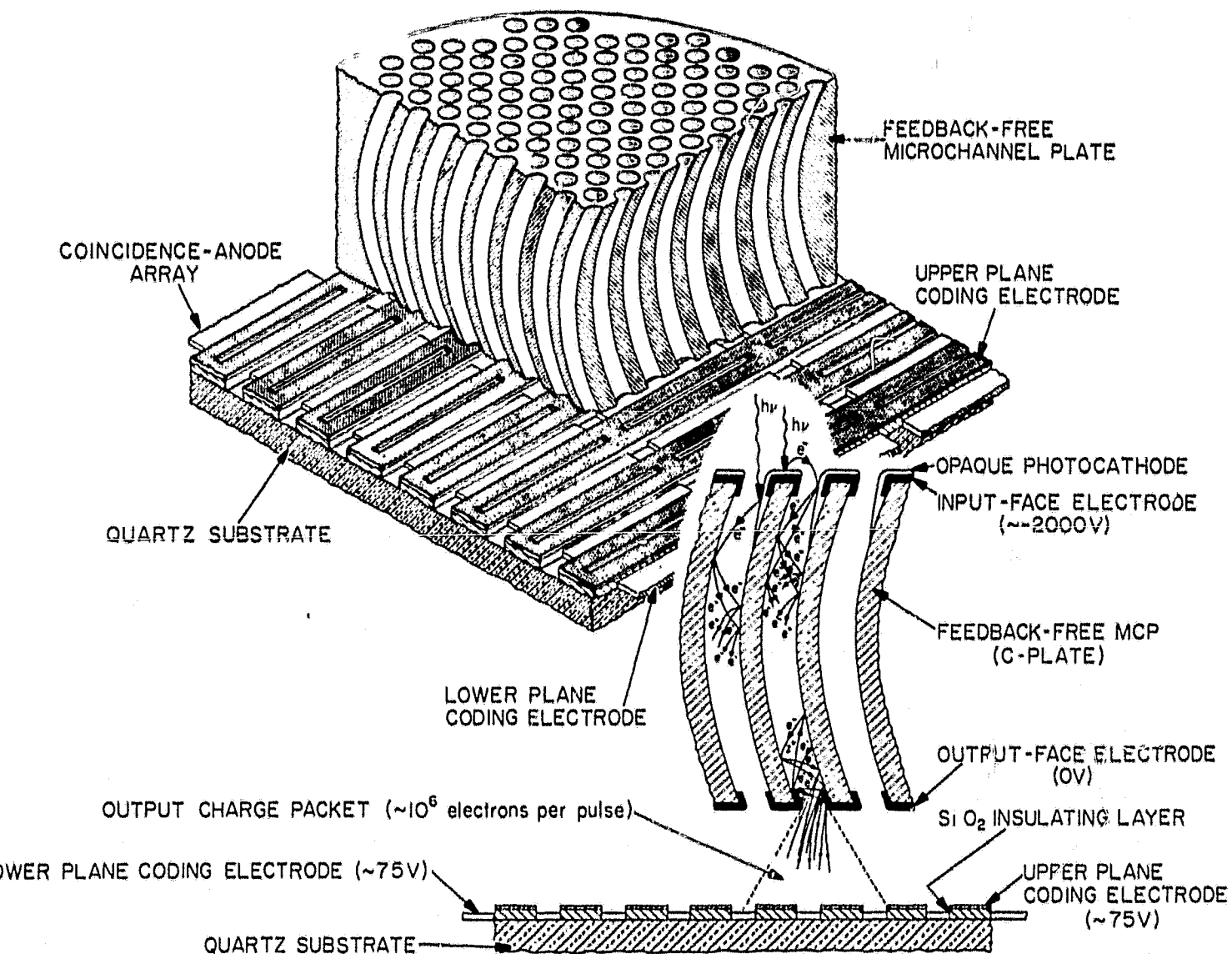
^a The listed central wavelength are the wavelengths of maximum absorption depth. The uncertainties are roughly ± 1 Å.

^b The equivalent widths include photospheric lines, which appear not to contribute significantly.

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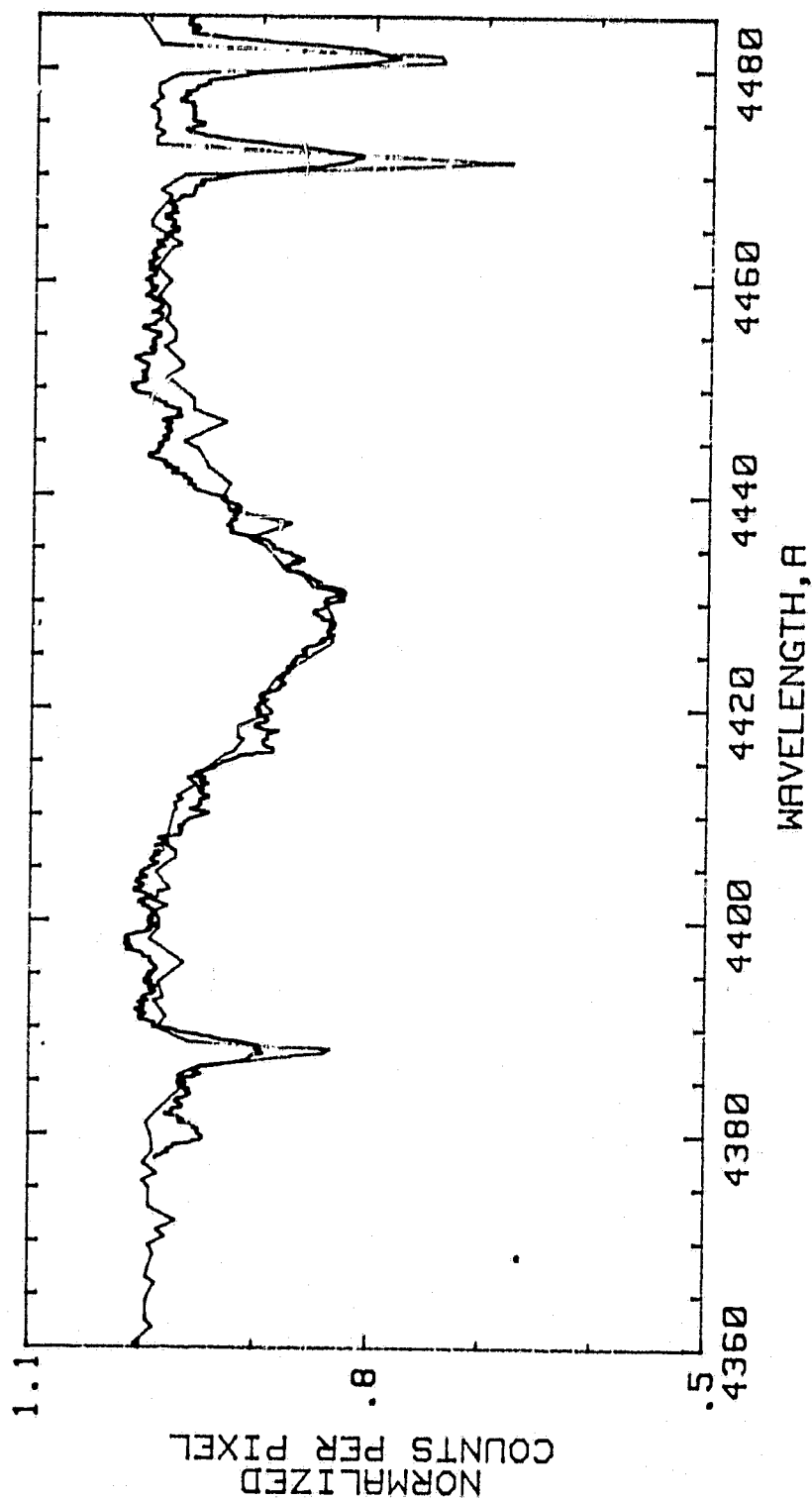
MULTI-ANODE MICROCHANNEL ARRAY

two-fold coincidence-anode array

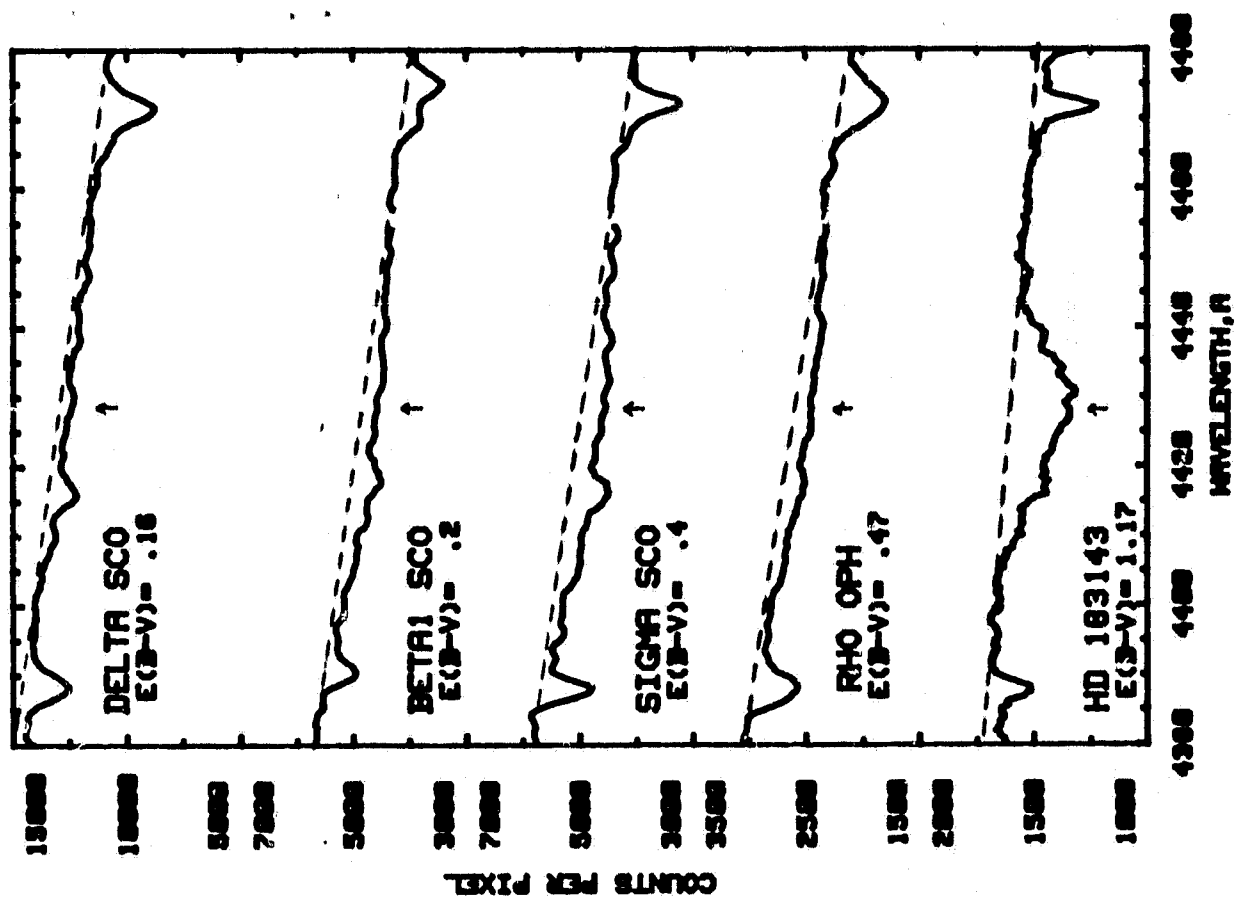


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