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RECENT DEVELOPMENTS IN THE APPLICATION OF THE FABRY-PEROT INTERFEROMETER TO SPACE RESEARCH

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Abstract. — For orbiting astronomical telescopes and rocket spectroscopy the great angular dispersion of the Fabry-Perot interferometer should permit easier guidance tolerance for a given spectral resolving power with the added profit of the physical compactness of an etalon spectrometer or spectrograph. Moreover the superiority in luminosity and illumination of the interferometer instruments would permit shorter exposures and greater time resolution.

Work aimed at extending the spectral range of the interferometer for high resolution work on the solar Fraunhofer spectrum (3 000 Å-1 800 Å) from stabilized rockets is reviewed. The first problem of producing suitable semi-reflecting coatings for the region $< 2\,400$ Å has now been solved by the development of magnesium fluoride overcoated aluminium films and the results obtained are illustrated with interferograms of $\lambda\,1\,849$ of Hg I and transmission curves of interference filters for the range 1 700 Å to 2 400 Å.

The development of an optically contacted air gap Fabry-Perot interferometer for rocket spectroscopy is also described. A recorded fringe finesse of 30 for a 2 cm aperture has been obtained at $\lambda\,5\,461$ with this instrument, and the adjustment remains constant with time.

Finally, two rocket experiments to study the resonance lines of Mg II at 2 795 and 2 802 Å are described. The first experiment will comprise a Fabry-Perot interferometer crossed with an échelle spectrograph to give a spectral resolution in the fringes of about 0.03 Å at 2 800 Å with a solar spatial resolution of 10 seconds of arc radially.

The second experiment will employ a scanning Fabry-Perot interferometer, also crossed with an échelle, with photoelectric detection.

Résumé. — Pour les télescopes en orbite et pour la spectroscopie en fusée la grande dispersion angulaire de l'interféromètre Fabry-Perot devrait permettre des tolérances de guidage moins sévères pour un pouvoir de résolution donné, avec l'avantage supplémentaire dû aux dimensions réduites de l'étalon. De plus le gain de luminosité des appareils interférentiels permettrait des poses réduites et une meilleure résolution dans le temps.

Nous passons en revue le travail accompli afin d'étendre le domaine spectral de l'étalon pour l'étude à haute résolution des raies solaires de Fraunhofer (3 000 Å-1 800 Å) à partir des fusées stabilisées. Le premier problème est la production de couches semi-réfléchissantes pour la région $\lambda < 2\,400$ Å. Il a été résolu par le développement de films d'aluminium recouverts de fluorure de magnésium ; les résultats obtenus sont illustrés par des interférogrammes de la raie 1 849 Å de Hg I et par des courbes de transmission de filtres interférentiels pour le domaine 1 700 Å-2 400 Å.

La réalisation d'un Fabry-Perot à lame d'air avec séparateurs en contact optique pour spectroscopie en fusée est ensuite décrite. Une finesse enregistrée égale à 30 pour une ouverture de 2 cm a été obtenue à 5 461 Å et le réglage reste stable en fonction du temps.

Enfin deux expériences d'étude des raies de résonance de Mg II à 2 795 et 2 802 Å à partir de fusées sont décrites. La première comprendra un interféromètre Fabry-Perot croisé avec un spectrographe à échelle capable de donner une résolution spectrale de 0,03 Å à 2 800 Å avec une résolution spatiale de 10 secondes sur le soleil. La seconde expérience utilisera un Fabry-Perot à balayage, également croisé avec une échelle, et une détection photoélectrique.

Introduction. — The Fabry-Perot interferometer has played a significant role in astronomical spectroscopy in the past. Thus Fabry and Perot themselves measured solar wavelengths as early as 1902 and investigated

the spectra of the great nebula of Orion in 1914. Since then the solar spectrum, auroral lines and nebular spectra have been studied by many observers. Apart from its unique use for the absolute determination of wavelengths the interferometer has a large gain in light gathering power over grating dispersers [1] and the realization of this has led to increasing use of

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the instrument for diagnostic spectroscopy of plasma sources [2, 3]. For orbiting astronomical telescopes and rocket spectroscopy the superiority in luminosity and illumination of the interferometer is equally important.

In many astrophysical problems involving line profile determinations a resolving power of $10^5 - 10^6$ is required and the echelle and Fabry-Perot interferometer are the only two dispersers capable of providing this type of resolution and, for a given resolving power the Fabry-Perot interferometer is two orders of magnitude more luminous than an echelle instrument [1]. Moreover, in the far ultraviolet below about $2\,500\text{ \AA}$ the resolving power of the echelle falls rapidly because satellite intensities near line centres are increasing and scattered light begins to intrude [4]. Dunham [5] first pointed out how this luminosity gain could be exploited for ground based stellar spectroscopy and the same argument applies to the orbiting telescope case where the seeing is now replaced by guidance limitations, with the added profit of the physical compactness of an etalon spectrometer due to its great angular dispersion. Thus, for a spectral resolving power of 10^6 the guidance requirement need be only ± 5 minutes of arc. Alternatively, for a given guidance system the resolving power could be increased by about two orders of magnitude over a grating instrument, without affecting the performance.

The Fabry-Perot spectrograph has also greater illumination than grating or prism instruments of equal resolving power [1], and the greater angular dispersion reduces the demands made on the linear resolution of detectors. This is particularly important for space research applications if image tubes, including T. V. camera tubes, are to be employed. Thus a tube having a linear resolution of only 2 line pairs per millimeter would still permit a spectral resolving power of 10^4 for a camera focal length of 30 cm employing the second Haidinger ring, assuming a finesse of 10. A channelled image intensifier should then provide adequate spatial resolution. Figure 1 shows an interferogram recorded by a developmental channelled image intensifier [6] with a camera focal of 30 cm length, 0.5 mm diameter channels gave an effective resolving limit of 1-2 line pairs/mm. The gain of this experimental tube was not very uniform, but the result indicates the potential of the interferometer, simple image tube combination.

Extension of spectral range of the interferometer. — To undertake high resolution work on the solar Fraunhofer spectrum from $3\,000-1\,800\text{ \AA}$ it was decided in 1961 to investigate the possibility of extending

the spectral range of the Fabry-Perot interferometer as far in to the ultraviolet as possible. The two factors which previously limited extension of the spectral



FIG. 1. — Interferogram recorded by channelled image intensifier. Spectral resolving power 10^4 .

range were the transmission and optical finish of interferometer flats and the availability of suitable reflecting coatings. Fused quartz now commercially available has a transmittance $> 50\%$ down to $1\,670\text{ \AA}$ for a 5 mm path required for a Fabry-Perot flat and if polished with care a surface finish of r.m.s. roughness of approximately 3 \AA can be achieved. Etalon plates can be easily worked to match better than $\lambda/150$ in the green over 6 cm diameter and a defects finesse in the range 16-24 is then attainable with flats transmittings a useful fraction of the light in the spectral region $1\,600-2\,400\text{ \AA}$.

The chief obstacle was in obtaining suitable reflecting coatings. While for wavelengths $> 2\,400\text{ \AA}$ there is a wide range of suitable coatings [1], no high index material transmitting $< 2\,400\text{ \AA}$ suitable for multi-layer dielectric coatings is available. However, recently we have developed aluminium-magnesium fluoride coatings [7] for the spectral region $< 2\,400\text{ \AA}$ and reflecting coatings are now available for wavelengths $> 1\,800\text{ \AA}$. Figure 2 shows a plot of transmission τ_A , versus reflecting finesse, N_R , for various aluminium coatings at $\lambda\,1\,850$ compared with performance at $4\,000\text{ \AA}$. The influence of evaporation pressure for

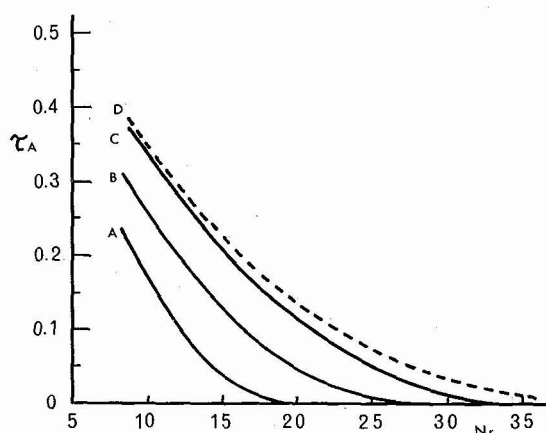


FIG. 2. — Al and Al — MgF₂ reflecting coatings.

Curves A : Al evaporated at 10^{-5} mm Hg } 1850 \AA
 B : Al — 10^{-7} mm Hg }
 C : Al-MgF₂ at 1850 \AA
 D : Al at 4000 \AA

pure aluminium is clearly shown and semi-transparent aluminium overcoated with magnesium fluoride has a performance at $\lambda 1850$ comparable with that of the highest quality aluminium coatings [8] at 4000 \AA . Moreover, the optical properties of these magnesium fluoride overcoated aluminium films remain stable over long periods. It should be remembered that much hyperfine structure and absolute wavelength determination work has been carried out in the past at longer wavelengths with coating of poorer performance than our present aluminium-magnesium fluoride coatings at 1800 \AA .

As an example of what is now possible, figure 3



FIG. 3. — Interferogram of $\lambda 1849 \text{ \AA}$ of $^{198}\text{Hg I}$.

shows an interferogram of $\lambda 1849 \text{ \AA}$ of $^{198}\text{Hg I}$ obtained with coatings of 80 % reflectivity. This interferogram was recorded on Q plates in a specially designed vacuum spectrograph. This instrument which has both prism and grating dispersing systems was constructed to test interferometers to be subsequently flown in Skylark rockets. Both the collimator and camera side tubes, of 10 inch diameter, have optical bench mounts for easy insertion and adjustment of an interferometer. Figure 4 shows fringes of the same

line of natural mercury obtained from a « Spectroline » 11 Sc-1 lamp. The centre absorption is clearly visible.

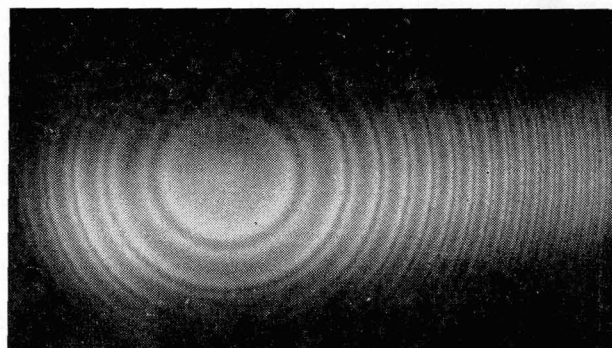


FIG. 4. — Interferogram of $\lambda 1849$ of natural Hg.

Far ultraviolet interference filters. — The $\lambda 1849$ line of figure 4 was isolated by two interference filters [9] specially produced in our laboratory for this wavelength. These first order filters (Fig. 5) consist of two

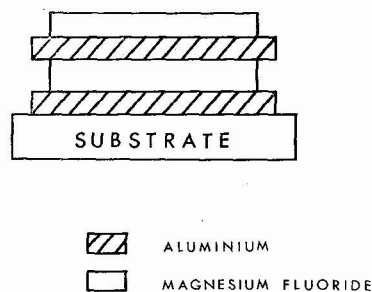


FIG. 5. — Schematic diagram of aluminium — magnesium fluoride — aluminium interference filter.

aluminium reflecting layers separated by a magnesium fluoride spacer layer of optical thickness (nd) given by

$$nd = (\lambda_0/2\pi) [(m-1)\pi + \beta], \quad m = 1, 2, \dots$$

where m is the order of interference ($m = 1$ representing a filter of minimum spacer thickness, a so-called first order filter, β is the absolute phase change on reflection at the magnesium fluoride-aluminium boundaries and n is the refractive index of the dielectric spacer layer). The outer magnesium fluoride overcoating layer serves two functions. In addition to preventing oxidation of the second aluminium film it also acts as an antireflecting layer and so increases the filter peak transmission. This requires a final dielectric layer of optical thickness

$$nd = \lambda_0 \beta/4\pi.$$

Transmission curves for a number of first order filters are shown in figure 6. These filters were deposited onto

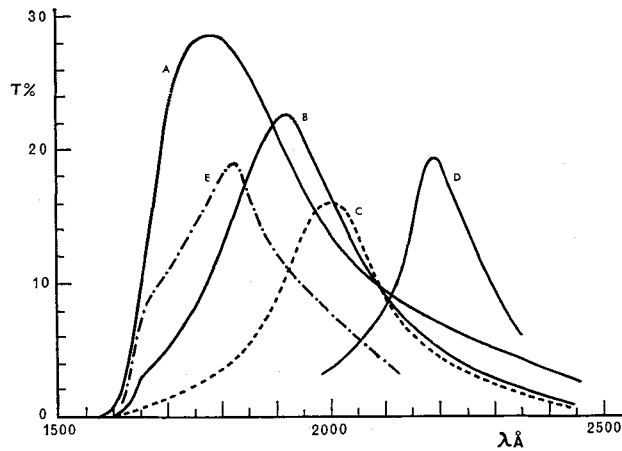


FIG. 6. — Experimental transmission curves of first order filters deposited on Spectrosil B substrates.

fused silica « Spectrosil B » substrates of either 1 or 2 mm thickness. The spacer layer of filter A was chosen to give a peak transmission at a wavelength of about 1725 Å. However, the actual peak occurs at λ 1680 Å due to the effect of increasing absorption in the Spectrosil substrate. Figure 7 shows a first order filter depo-

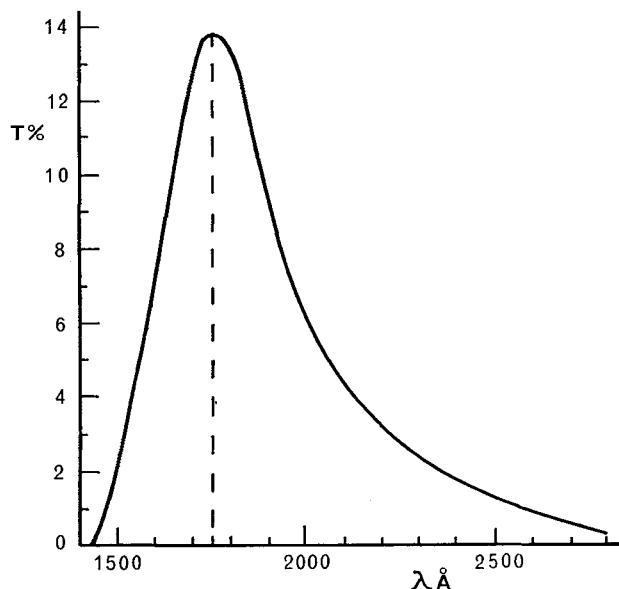


FIG. 7. — Experimental transmission curve of a first order filter deposited on a sapphire substrate.

sited on a sapphire substrate of 1 mm thickness. A narrower bandwidth would be obtained with a thinner spacer layer. The consequent shift of the transmission

peak to a shorter wavelength would lead to the properties of the filter being largely determined by the properties of the reflecting layers at wavelengths greater than the peak wavelength and by the substrate absorption at shorter wavelength. An improved performance over that shown in figure 7 could also be expected from a filter on a lithium fluoride substrate because of its higher transmission.

Rocket Interferometry. — The resonance lines of Mg II at 2795 and 2802 Å are particularly important for studies in solar physics. It is proposed to make a detailed study of the profiles of these lines and their distribution over the solar disc. Two experiments are to be carried out which will be a joint effort by Royal Holloway College and U. K. A. E. A. Culham Laboratory. Both these experiments will require a sun pointing stabilized Skylark rocket and will include a Culham fine optical alignment system operating on a collector mirror to maintain the solar image to an effective pointing accuracy of ± 5 seconds of arc.

The first experiment will comprise a Fabry-Perot interferometer crossed with an echelle spectrograph. The system will be optimized for the Mg II lines to give a spectral resolution in the fringes of about 0.03 Å at 2800 Å. The echelle slit will be set to give a resolution limit of 0.25 Å and each echelle line will be recorded photographically and the alignment system programmed so as to move the interference fringes across the solar image in a series of exposures to give a wide spatial coverage. Spatial resolution will be 10 seconds of arc radially and along a solar arc it will depend upon the rocket roll, but it is hoped to achieve 2 degrees of arc. In addition to the data on the Mg II lines a spectral range of about 100 Å centered at 2800 Å will be photographed with the same spectral and spatial resolutions. The optical arrangement of the echelle-interferometer rocket spectrograph is shown in figure 8. The prism pre-disperser isolates one free spectral range of the echelle (300 grooves per mm).

The second experiment will employ a scanning Fabry-Perot interferometer, also crossed with an echelle spectrometer, but exploiting the high luminosity of the centre fringe by scanning through many line profiles and recording photoelectrically with solar blind photomultipliers. From the expected solar flux it is estimated that a scan time of 0.1 seconds will be needed to record the emission line profiles with a resolution of 0.03 Å. A Raven 6 A rocket motor would permit an effective observing time above 100 Km of 300 seconds and hence 3×10^3 spatial resolution elements of 10×10 seconds of arc could be covered

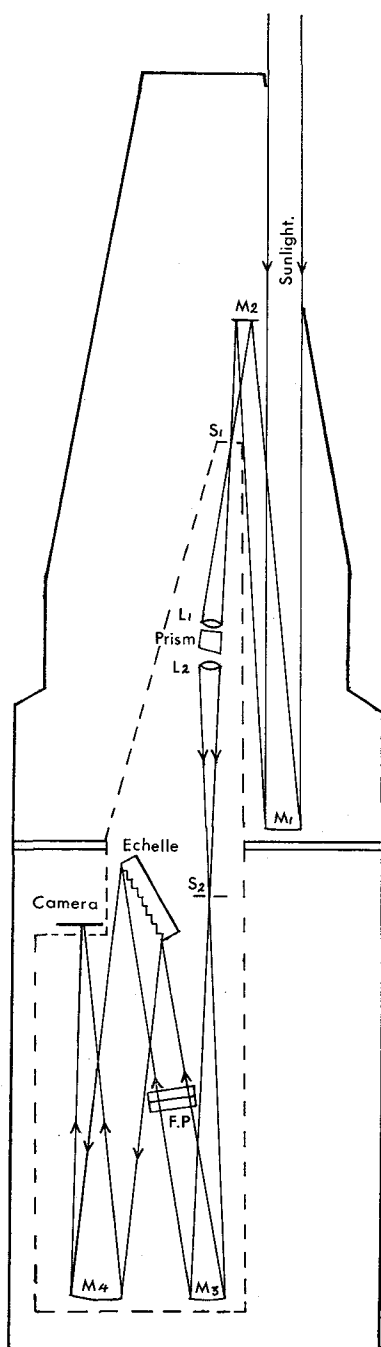


FIG. 8. — Optical arrangement of echelle-interferometer rocket spectrograph.

during a single flight. This corresponds to 10 % of the solar disc. The Culham alignment system will be programmed to cover the most active region of the sun at the time of observation.

It is planned to fly the first experiment in september, 1967 the second experiment the following year.

Optically contacted interferometer. — A permanently adjusted etalon is essential for the rocket spectrograph. Solid interferometers (10) have been reported in the past but it is not possible to optically work the faces of a glass or quartz block of sufficient aperture to be both flat and parallel to the required accuracy. This is particularly true if the interferometer is to be used in the far ultraviolet ($< 3\,000 \text{ \AA}$), since the surface finish requirements increase linearly with the decreasing wavelength, and it would be necessary for many experiments to have the faces parallel and flat to better than $\lambda/150$ in the green. Also any inhomogeneity of the material would result in a lower defects finesse. In addition the reflectivity at the quartz-reflecting coating interfaces would be less than for an air gap instrument. Thus if aluminium-magnesium fluoride overcoatings were employed at say $\lambda\,1\,850$ the effective reflectivity would be reduced by about 2 %. This would result in a reduction of the reflecting finesse from 16 to 14 and for the interferometer transmission from 20 % to 16 %.

An optically contacted 10 cm air gap etalon has been previously employed in the near infrared [11] but the recorded fringe finesse obtained was not reported. For a 10 cm gap it would not have been possible to measure the instrumental profile with the light sources then available.

An interferometer spacing of 0.4 mm (free spectral range of $\sim 1 \text{ \AA}$) and a clear aperture of 3 cm is required for the solar spectrograph etalon. The plates of Spectrosil A, of 6 cm diameter and 1 cm thick, are matched to better than $\lambda/180$ over their full physical aperture. The 0.4 mm thick 6 mm diameter cylindrical Spectrosil spacers were cut out from selected portions of a large plate, worked flat and parallel to better than $\lambda/40$ over a distance of 4 cm, and optically contacted to both plates at angular intervals of 120 degrees.

Before optically contacting the assembly, the central 3 cm of each of the interferometer plate surfaces were coated with silver films overcoated with a thin layer of magnesium fluoride to prevent oxidation.

Figure 9 shows the resulting fringes of the $\lambda\,5\,461$ line of an 198 Hg source for a 2 cm etalon aperture. The corresponding microdensitometer trace (linear in density, 0.087 cm^{-1}) is shown in figure 10. From this a recorded fringe finesse of 30 was derived. If the aperture is increased to 2 cm the fringe finesse decreases to 22 while an aperture of 1 cm gives a finesse of 43. The adjustment has remained stable for a period of two

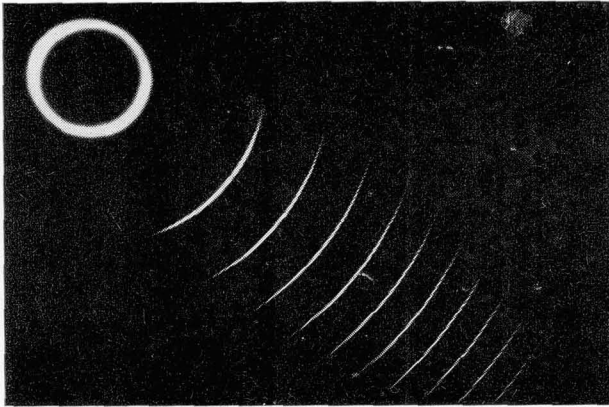


FIG. 9. — Optically contacted interferometer fringes (λ 5 461 Hg I), 2 cm etalon aperture.

months to date. This decrease in recorded fringe finesse with increasing aperture is due to a slight wedge effect. This probably arises from incomplete optical contact over the full area of one of the spacers as can be observed visually.

If the fixed gap etalon is placed in a conventional mount with spring adjustments, the wedge can be eliminated with very small differential spring pressure and a recorded finesse of ~ 50 is then obtainable. Under these conditions the adjustment also remains stable.

Discussion. — The main advantages of the Fabry-Perot interferometer for space research are as follows :

- 1) Absolute wavelength measurement is obtained,
- 2) It is much faster than other dispersers for the same resolving power,
- 3) Its great angular dispersion leads to a compact instrument and easier guidance demands.
- 4) Its greater luminosity permits rapid scanning of line profiles and the required techniques are already available from plasma and laser work.

5) It provides a means of obtaining high resolving powers of 10^5 - 10^6 not yet obtainable by other means, without undesirable instrumental line wings, in the spectral region 1 800-3 000 Å.

The proposed Skylark rocket experiments, in addition to providing valuable astrophysical results, should test the feasibility of interference spectroscopy for space research. A further satellite borne « Solar patrol » interferometer experiment to study rapidly changing areas of the disc is now being considered. A scanning interferometer could also be used to study the Magnesium II doublet in stellar spectra.

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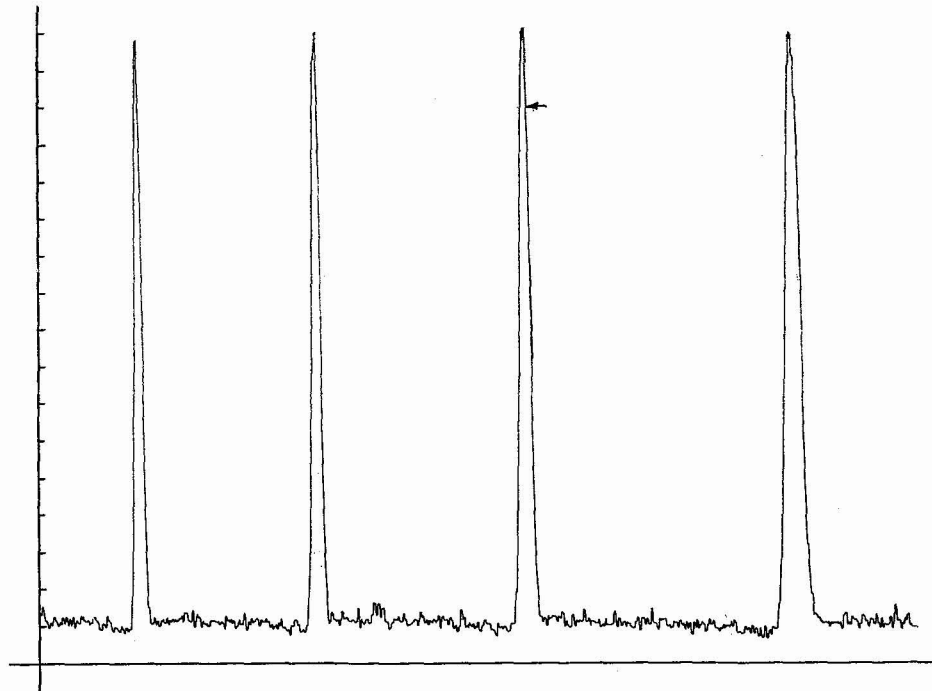


FIG. 10. — Microdensitometer trace of figure 9.

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