CR 112845

A NEW TECHNIQUE FOR MEASURING OSCILLATOR STRENGTHS IN THE UV

R. A. Day

Department of Physics, University of Oklahoma, Norman, Oklahoma 73069

NGR-37-003-047
NGR-37-003-026

INTRODUCTION

Physicists have long been concerned with the measurement and compilation of atomic and molecular oscillator strengths(1). These measurements are always difficult but in the vacuum UV the ordinary problems are enhanced by the lack of adequate comparison sources and by the great optical thickness of the spectral lines involved. Ingenious techniques have been developed for emission measurements by Lincke and Griem(2); more standard absorption techniques have been used by a number of investigators(3). One technique which is ideally suited for the measurement of optical constants of strongly absorbed spectral lines is the "hook" method of Rhozdestenskii which samples the anomalous index of refraction in the neighborhood of spectral lines(4,5). This technique uses a Mach-Zehnder interferometer (or sometimes a Fabry-Perot) to create a set of fringes which are displaced by the variation of optical path lengths in the vicinity of a spectral line. This technique, however, fails in the vacuum ultraviolet because of the absence of transmitting materials to use as beam splitters.

Alternative devices can be considered; for example, a Lloyd's mirror type interferometer is in principal possible; however, the Mach Zehnder derives its sensitivity from the use of high orders of interference, a requirement which is impractical for Lloyd's mirror arrangements.

Another possibility is given by a new interferometer which has no transmitting elements[6], but does have the advantage of multiple beams. The present paper describes an arrangement of this interferometer which has important possibilities for use in the measurement of atomic and molecular energy level populations and oscillator strengths in the vacuum ultraviolet.

Interferometer Arrangement

The GIMBI[6] utilizes the interference between a set of multiple beams to produce a set of fringes in the exit plane of the interferometer. The amplitude in the exit plane is[6]:

$$\phi = b_o \sum_{n=-N}^{+N} (-1)^n \, r^{|n|} \, \exp\{ik\sqrt{L^2+(nt-a)^2}\} \quad (1)$$

and since grazing incidence reflections are used, $r \simeq 1$. Furthermore, the expansion

$$L\sqrt{1+(\frac{nt-a}{L})^2} \simeq L\{1 + \frac{1}{2}(\frac{nt-a}{L})^2 - \frac{1}{8}(\frac{nt-a}{L})^4 + \ldots\} \quad (2)$$

can be limited to two terms if $\frac{nt}{L} \ll 1$. If we utilize only modes on axis, i.e. $a = 0$, then the fringe maxima occur whenever

$$\frac{kt^2}{2L} = m\pi \quad . \quad (3)$$

Consider a direction perpendicular to the axis, parallel to the interferometer plates. The effect of moving the observation point in this direction is equivalent to the substitution of $\sqrt{L^2+Z^2}$ for L.(Fig. 1) Then we can state the more general resonance condition

$$\frac{kt^2}{2\sqrt{L^2+Z^2}} = m\pi$$

or (4)

$$\frac{t^2}{\lambda} = m\sqrt{L^2+Z^2} \quad .$$

Now, if the interferometer is positioned in front of a stigmatic spectrograph so that the entrance slit coincides with the plane (a=0,Z) of the interferometer, then the exit plane of the spectrograph will show a set of banded fringes, where the fringe positions are solutions to the equation

$$m = \frac{t^2}{\lambda\sqrt{L^2+Z^2}} \tag{5}$$

with m integer. These solutions are symmetrical with respect to the point Z=0 and Fig. 2 shows a sketch of the fringes in the region around 1000 Å for an interferometer of length 3 cm and plate separation 1 mm. The fringe sharpness is, of course, increased when the number of beams contributing to the interference pattern is large. However, the fringe position is independent of the number of beams. Thus, in this region around 1000 Å, the order number of interest will be near 330 depending only on t, L and Z.

Interferometer Parameters

The usual quantities which describe interferometer performance can be ascertained, e.g. the free spectral range (the change in wavelength equivalent to a change in order number of 1) is

$$1 = \Delta m = -\frac{\Delta\lambda}{\lambda_o^2}\frac{t^2}{\sqrt{L^2+Z^2}} \tag{6}$$

or

$$\Delta\lambda_1 = -\frac{\lambda_o{}^2}{t^2}\sqrt{L^2+Z^2} \tag{7}$$

and for $Z = 0$

$$\Delta\lambda_1^0 = -\frac{\lambda_o^2}{t^2} L \quad . \tag{8}$$

For the specifications quoted above the fringe separation is approximately 3Å.

Another parameter, the separation between fringes as a function of distance from the point of symmetry can also be described. Using

$$L^2+Z^2 = \frac{t^4}{\Delta^2 m^2} \tag{9}$$

$$\Delta(Z^2) = \frac{t^4}{\lambda^2 m^2}\,\Delta m \tag{10}$$

Fringes in the Neighborhood of a Spectral Line

The above considerations have all been for a vacuum; i.e. n, the index of refraction, is taken to be equal to one. However, in the presence of a medium, the index of refraction will not be one, but will rather have contributions from electrons, neutral particles and also resonant features of the spectrum. In particular, in the neighborhood of spectral lines, the index of refraction has the anomalous behavior[5],

$$n^2-1 = \frac{e^2}{2\pi m_e c^2} N_\ell \lambda_o^{\,3} \left(\frac{\lambda-\lambda_o}{W^2+(\lambda-\lambda_o)^2}\right) f_{\ell u} \quad . \tag{11}$$

In this relation, e is the charge of the electron, $m_e c^2$ is rest mass energy of the electron, λ_o is the wavelength of the spectral line resulting from the transition from a lower to an upper state, $f_{\ell u}$ is the oscillator strength of the transition, N_ℓ is the number of atoms in the lower state and W is the width of the spectral line. The importance of this equation to us lies in the dependence of the right hand side of the equation on the parameters N_ℓ and $f_{\ell u}$. We will utilize this relation far away from the spectral line where

$$\lambda-\lambda_o >> W$$

so that an appropriate form here is:

$$n^2-1 = \frac{A}{\lambda-\lambda_o} \tag{12}$$

and A is a parameter depending on number density and oscillator strength lying in the range 10^{-4} to 1 cm. We will pick A to be .1 later for exhibiting the distortion of fringes due to the presence of a spectral line. This value is a bit high and the fringes are consequently affected at very large distances from the spectral line but the intention here is simply to exhibit the principle. Then using the index of refraction explicitly one obtains

$$L^2+Z^2 = \frac{t^4}{m^2 \frac{\lambda^2}{n^2}}$$

or

$$L^2+Z^2 = \frac{t^4}{m^2\lambda^2} \left(1+ \frac{A}{\lambda-\lambda_o}\right) \tag{13}$$

and the important measurable quantity, the free spectral range can be found using

$$m \simeq \frac{t^2}{\sqrt{L^2+Z^2}\,\lambda} \left\{1 + \frac{1}{2} \frac{A}{\lambda-\lambda_o} \right\} \tag{14}$$

and for $\Delta m = 1$

$$\Delta_1 \simeq \frac{\lambda^2 \sqrt{L^2+Z^2}}{t^2} \left\{1- \frac{A}{2(\lambda-\lambda_o)} - \frac{A\lambda}{2(\lambda-\lambda_o)^2} \right\} ; \tag{15}$$

at wavelengths greater than 100 Å the middle term in the braces can be ignored.

And, the fringe spacing in the neighborhood of a spectral line is

$$\Delta_1 \simeq \Delta\lambda_1 \left\{1- \frac{A\lambda}{2(\lambda-\lambda_o)^2} \right\} \tag{16}$$

i.e. the effect of the index of refraction is essentially magnified by the ratio $\lambda/(\lambda-\lambda_o)$, a number normally on the order of 1000. The fractional reduction of the fringe spacing is symmetrical on either side of the spectral line and can be expressed as

$$\frac{\Delta_1-\Delta\lambda_1}{\Delta\lambda_1} = - \frac{A\lambda}{2(\lambda-\lambda_o)^2} \quad . \tag{17}$$

Then a measure of the product of oscillator strength and population density of the gas between the interferometer plates is effected by measuring the fractional change in the fringe spacing. This technique is very attractive because Δ_1, $\Delta\lambda_1$, λ and $(\lambda-\lambda_o)$ are all quantities whose measurements should be possible within a few per cent.

Another possible measurement is provided by the vertical distance between fringes; then

$$\Delta(Z^2) = -\frac{2t^4}{\lambda^2 m^3}\left(1+\frac{A}{\lambda-\lambda_o}\right)\Delta m \tag{18}$$

with all the quantities measureable except for A. The usefulness of this approach is limited by the height of the fringes, and will in general probably be less than the method utilizing the change in the free spectral range.

Specific Case.

Figure 2 illustrates the fringes in vacuum (lower part of the figure) and in the presence of a spectral line (upper part of the figure). The parameters used in this sketch are:

$$L = 3 \text{ cm}$$
$$t = 1 \text{ mm}$$
$$\lambda_o = 1000 \text{ Å}$$
$$A = .1$$

Then the figure plots Z vs. λ for constant m where m is on the order of 330. The value of A chosen is large and results in a distortion of the fringe positions and shapes as far away as 20 Å from the spectral line. Actual cases will reduce this effect considerably. The m value of the fringe is listed next to the fringe at the top and bottom. Note that 300 must be added to the number given i.e. 23 is actually 323.

Note that for clarity only a representative sample of fringes are sketched. However, the anomalous behavior of the fringes near the spectral line is clearly evident; also the symmetric clustering of the fringes around the spectral line is portrayed.

Summary

We have described the use of an interferometer to measure the product of oscillator strength and number density of absorbers. This technique should have unique applications in the vacuum UV.

Acknowledgments

This work was supported in part by two National Aeronautics and Space Administration Grants NGL-37-003-026 and NGR 37-003-047.

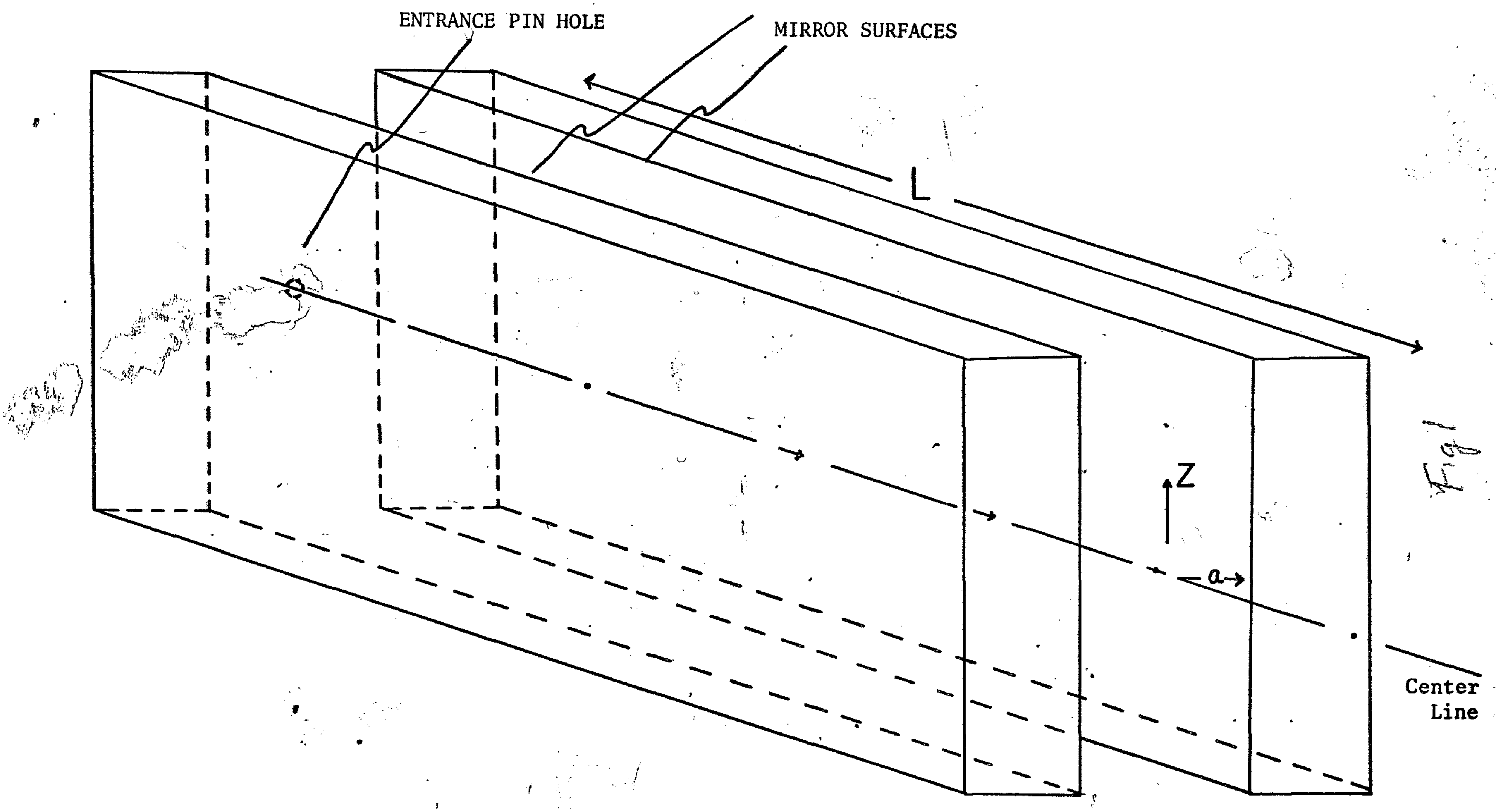
REFERENCES

1. W. L. Wiese, M. W. Smith and B. M. Glennon in NSRDS-NBS4 (1966).
2. R. Lincke and H. R. Griem, Phys. Rev. 143, 66 (1966).
3. A review of these techniques can be found in "Spectroscopy in the Vacuum Ultraviolet" by W.R.S. Garton in Advances in Atomic and Molecular Physics, Vol. 2, Ed. D. R. Bates and I. Estermann, Academic Press 1966.
4. W. C. Marlow, Appl. Optics 6, 1715 (1967).
5. E. W. Foster, "The Measurement of Oscillator Strengths in Atomic Spectra", Prets. Prog. in Phys. XXVII, 469 (1964).
6. R. A. Day, Appl. Optics 9, 31 (1970).

FIGURE CAPTIONS

Figure 1. This shows the interferometer illuminated through a pinhole by light having a continuous spectrum. The fringes appear along the Z direction at the exit plane of the interferometer.

Figure 2. Sketch of the fringes as they would appear in the exit plane of a stigmatic spectrograph. The lower part of the figure shows the fringes as they would occur in the absence of a spectral line. The fringes in the upper part of the figure are distorted by the presence of a spectral line. See text.



ENTRANCE PIN HOLE
MIRROR SURFACES
L
Z
a
Center Line
Fig 1

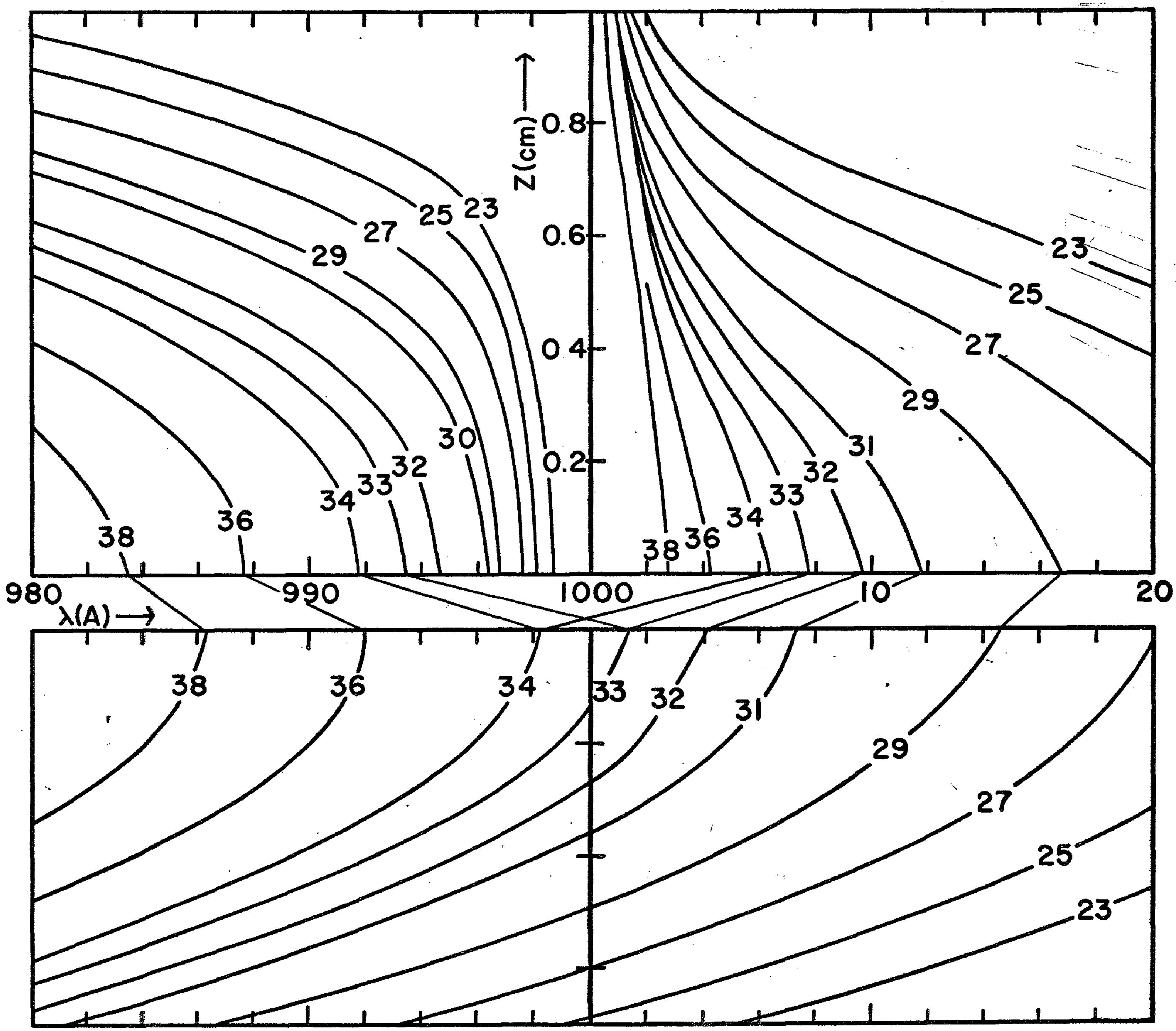

Z(cm) ⟶
0.8
0.6
0.4
0.2
23
25
27
29
30
31
32
33
34
36
38
980
990
1000
10
20
λ(A) ⟶
38
36
34
33
32
31
29
27
25
23

Fig 2