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STRUCTURAL AND SPECTRAL STUDIES OF SUNSPOTS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Annual Report

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of
The Franklin Institute
Swarthmore, Pennsylvania
19081

Submitted: September 29, 1971

I. Instrumentations and Observations

a) The Bartol Observatory

During the fall of 1970 the Harvard Observatory Council formally approved a loan, for an indefinite period of time to Bartol, of their 24-inch Clark reflector, which was "retired" in 1966. The telescope is of the broken Cassegrain type whereby the exit beam by a third mirror is deflected at right angles to the optical axis instead of exiting through the conventional Cassegrain hole in the primary mirror. The telescope will yield a solar image 5 inches in diameter, which is 2.5 times larger than our present image and which will enable us to study the heating effect in the upper atmospheric layers of considerably smaller spots than the presently observed ones.

After this decision was made by Harvard, the Board of Managers of The Franklin Institute agreed to make special funds available for housing this splendid long-term loan and for erecting an observatory on top of Bartol's building on the Swarthmore College campus. This loan suddenly makes possible long-cherished hopes for our own in-house installation with which to make observations with our spectrum scanner. Consequently a considerable effort has gone into the preliminary planning of how to utilize the reflector in an efficient and economic manner, which is commensurable with our special needs.

Seeing tests have been carried out on the roof of the Bartol building, which is about 50 feet above ground. Most solar and stellar installations are currently placed at such heights in order to eliminate the detrimental seeing effects of local air currents at ground level. A 6-inch refractor (f/15) kindly furnished by Sproul Observatory of Swarthmore College, has been securely mounted to the roof through a heavy baseplate.

Daytime seeing observations were carried out this fall with the projection of sunspot structures on a white board through the use of a wide angle Erfle eyepiece. Image sharpness of the spots were as good or better than at the Flower and Cook Observatory, where our present sunspot observations are being carried out. Excessive image motions due to building vibrations were never observed.

This same conclusion holds for the night time seeing tests. The resolution of double stars and estimates of general image definition and steadiness were found to be very well correlated with seeing estimates carried out simultaneously at the adjacent Sproul Observatory on the college campus. These combined results, we feel, warrant the placement of the telescope on top of the roof of the Bartol building, as earlier conceived.

Since our spectrum scanner requires a stationary focus at its entrance pinhole aperture and the scanner is too heavy to be mounted on a moving telescope, a stationary installation of the 24-inch reflector was an obvious requirement right from the beginning. The first design considered a horizontal siderostat solution like the present installation at the Flower and Cook Observatory of the University of Pennsylvania. A 24-inch flat mirror in an alt-azimuth mount directs the incoming light beam in a fixed horizontal direction. The beam of parallel light is imaged onto our scanner by a stationary and horizontally aligned 15-inch refractor.

However, such a siderostat arrangement involves a complex guidance system of the primary siderostat flat, either as at Flower and Cook Observatory by a mechanical system of shafts or alternatively driving the mirror by a computer servo loop. Optical encoders would sense the mirror attitude and feed this information to a minicomputer, which compares the observed attitude with a computed one and in turn sends an error signal to torque motors which rectify the attitude of the mirror. A visit to the National Radio Astronomy Observatory in Greenbank, West Virginia, and consultations with the U. S. Naval Observatory convinced us that this would be a very expensive solution - of the order of 30-50K - just for the computer steering system.

Although a horizontal beam arrangement is convenient, there is no major reason which precludes the use of the diagonal beam arrangement of polar siderostats, expecially since the broken Cassegrain of the 24-inch reflector permits a final horizontal exit beam to feed the scanner. Thus the polar siderostat and the inverted polar siderostat, i.e., heliostat, were in turn considered. Information was furnished by the Meudon Observatory of the University of Paris and the Brorfelde Observatory of the University of Copenhagen.

While the polar siderostat gives ready access to most parts of the sky, its incorporation in the existing Bartol building structure could not readily be made. The solution entails an expensive tower structure and an awkward coupling of the scanner. So, finally the decision has been made to adopt the heliostat system. A flat mirror of 36-inch diameter will be mounted on top of the existing Bartol roof and will direct the reflected beam down along the polar axis into the 24-inch reflector with its optical axis aligned with the polar axis (see Figure 1).

This arrangement permits an inexpensive roof housing for the heliostat and makes use of the existing space on the top floor of the Bartol building for the scanner and the 24-inch reflector. The heliostat solution eliminates the need for computer steering since the heliostat drive rate is the same as the Earth's diurnal rate. A further advantage accrues to polarization observations, (i.e., magnetometer observations) since for a given declination the instrumental polarization remains constant, independent of hour angle, which is not the case for conventional coelostats or horizontal siderostats. The sky accessibility is almost as good as for the horizontal siderostat and far better than for a coelostat.

All in all, we believe that the heliostat solution is by far the most inexpensive and readily implemented solution to our immediate observational needs. After negotiating with several telescope manufacturers (Davidson Optronics, Fecker of Owens-Corning and Group 128, Inc.) we have accepted the bid from Group 128, Inc. on the procurement of the 36-inch flat, mirror cell and drive mechanism. This firm recently manufactured a twin laser ranging telescope unit for the Smithsonian Astrophysical Observatory with very satisfactory results. During the summer, most of the smaller metal parts have been manufactured in our own machine shop as part of a collaborative venture with this firm. The heliostat is expected to be ready for shipment in December of this year.

Concurrently structural studies have been made of the roof of the Bartol building on the campus of Swarthmore College. As a result the designs for the heliostat mounting pad, the Clark telescope foundation and the heliostat housing have been completed. Work will be commenced on these units early this fall, with the expectation of completion by Christmas. Early next year the telescopes should be in operation, i.e. one year after the first decisions were made to build the Bartol observatory.

It is hoped eventually to incorporate into our installation a PDP-11 minicomputer which will interface with the scanner. This has long been a desirable development in our sunspot observational program. The computer will be able instantaneously to evaluate the umbral to disk continuum ratio for a particular time channel and to reject the printing of the channel if the ratio is outside a certain numerical range. The computer could also evaluate the cumulative counts in the different time channels and when it decides a certain preset precision has been reached in the total signal, it would turn off the counting system and direct the pressure generator or the grating drive to move to a new wavelength and start counting anew. By an oscilloscope display visual control of the running status of the build-up of a particular line profile could be attained. The possibility of a completely automatized line profile measuring sequence is thus at hand.

b) Umbral Continuum Intensities, Aureole Measurements and Theory

Attempts have been made to reduce the scattered light levels off the solar limb. The experiments were undertaken in the hope of reducing the present scattered light levels (0.5% of solar central disk intensity 1 minute of arc off the limb) to coronal intensity levels (0.1 to 0.01% of solar disk intensity) for studying the green coronal line over sunspots. A variety of baffles and occulting disks were constructed and interposed, none of which significantly reduced the scattered light contributions.

However, our observed scattered light levels compare quite favorably with those at other observatories. In Figure 2 is depicted for a variety of wavelengths the scattered light levels at varying distances from the solar limb. For comparison the aureole curve of Mattig (1971) has been included, which observation pertains to a wavelength of 6153Å. Mattig's observations were made with the domeless refractor of Kiepenheuer at Capri. It is an instrument especially designed for low scattered light levels and placed on a location believed to favor good seeing. Nevertheless, our scattered light levels with an aged mirror coating are only 0.1-0.2% higher than Mattig's values. With fresh mirror coatings our values at λ5890 are almost half of those of the Capri instrument.

There is a slight wavelength dependence in our aureole values, with a steepening of wavelengths shortward of λ4500.

Seasonal variations are secondary to the instrumental scattering effects.

The umbral continuum observations also compare favorably to those of other observers as evidenced in Figure 3. In this figure we have drawn as black triangles our continuum observations for the NaD_2 line region (λ5890). The observations are the result of about 120 separate continuum recordings of individual durations 0.8 seconds. The observations represents more than 100,000 umbral counts. Adopting Zwaan's rule of thumb for a multiplication factor of 5(Zwaan, 1965) to arrive at the scattered light correction at the center of the disk, the correction amounts to 2.5% of the central disk intensity. Mattig (1971) in his recent observations of the transit of Mercury adopts a value of about 2.2%. Since our Aureole curve is very similar in shape to that of Mattigs near the limb, we feel that our correction factor of 2.5% is quite realistic.

The same remarks pertain to our continuum observations in the blue (λ4260). Our continuum values are systematically higher than Mattig's estrapolated values by about the same intrinsic amount (0.030) or at λ5890. The extrapolated value of Maltby's (1970) observations agree better with ours at λ4260.

If we go to the extreme of 4% scattered light correction, we still cannot reach the low values deduced by Mattig. But at λ5890 our results (0.119) agree quite well with those of Stellmacher and Wiehr (1970, value 0.120) and also those of Henoux (1969, value 0.114). On the other hand no adequate model atmosphere can explain the low values of Mattig. The coolest umbral model yet proposed is that of Zwaan (1965). Dr. Yun has theoretically calculated with Zwaan's model the intensity ratios shown in Figure 3 (open circles with crosses). While the resulting values go a long way to explain Mattig's corrected observations, the Zwaan model yields much too strong absorption in the NaD_2 wings, which is absolutely incompatible with observations in medium sized spot (see Figure 4). The tentative conclusion then is that Mattig overcorrects for scattered light and that his continuum ratios should be revised upwards.

In this connection it becomes increasingly imperative to seek umbral intensity observations under conditions which more or less eliminate instrumental and atmospheric scattering. This could be done either by observations with existing coronagraphs (instrumental scattered light level are 0.003% of solar disk intensity) in mountain locations and coronal skies or better still on manned satellites such as the projected launch of Skylab in November 1972. Plans are under way for possible implementation of such projects.

One of the graduate students in Bartol's ongoing program of Graduate Studies in Physics and Astronomy, Mr. John Bower, (B.S. degree from M.I.T.), has begun a project to account for the shape of the observed aureole curves (exclusive of the seeing motion and the blurring factor) in terms of agglomerate particle diffraction patterns. Presently in aureole theory Gaussian and Lorentzian functions are used on an empirical basis with observationally determined shape factors, but with no deeper physical justifications. In Bower's attempts these parameters will be linked to particle size distributions or average particle sizes. Apart from easing the corrections of observed umbral intensities, the theory might become useful in studies of aerosol distributions over large cities. When one knows the instrumental scattering characteristics, the observations of solar aureoles through pollution layers over cities, might lead to a determination of the polluting particle sizes.

c) Auxiliary instrumentations.

During this period our auxiliary instrumental efforts have been somewhat set back in the loss of our instrumentalist, Dr. Theodore Fay, whose post-doctoral research fellowship terminated September 1, 1970. Dr. Michael Seeds of nearby Franklin and Marshall College joined our group temporarily and was responsible for the development of some auxiliary instrumentation, the principal of these being the construction of an optical multiple reflection device to improve the quantum efficiency of photomultiplier tubes.

Dr. Seeds successfully demonstrated gains by a factor of 2 in quantum efficiency at λ5890, which corroborates the findings of Oke and Schild (1968). This is equivalent to an increase of 40% of the effective telescope aperture at the cost of a few dollars!

Dr. Seeds also investigated various aspects of the instrumental profile and polarization of our echelle scanner and developed a simple and useful guider for sunspot and stellar observations. Studies were also made of the optimization of signal to noise ratios in our electronics pulsecounting equipment with the conclusion that our present equipment needs upgrading.

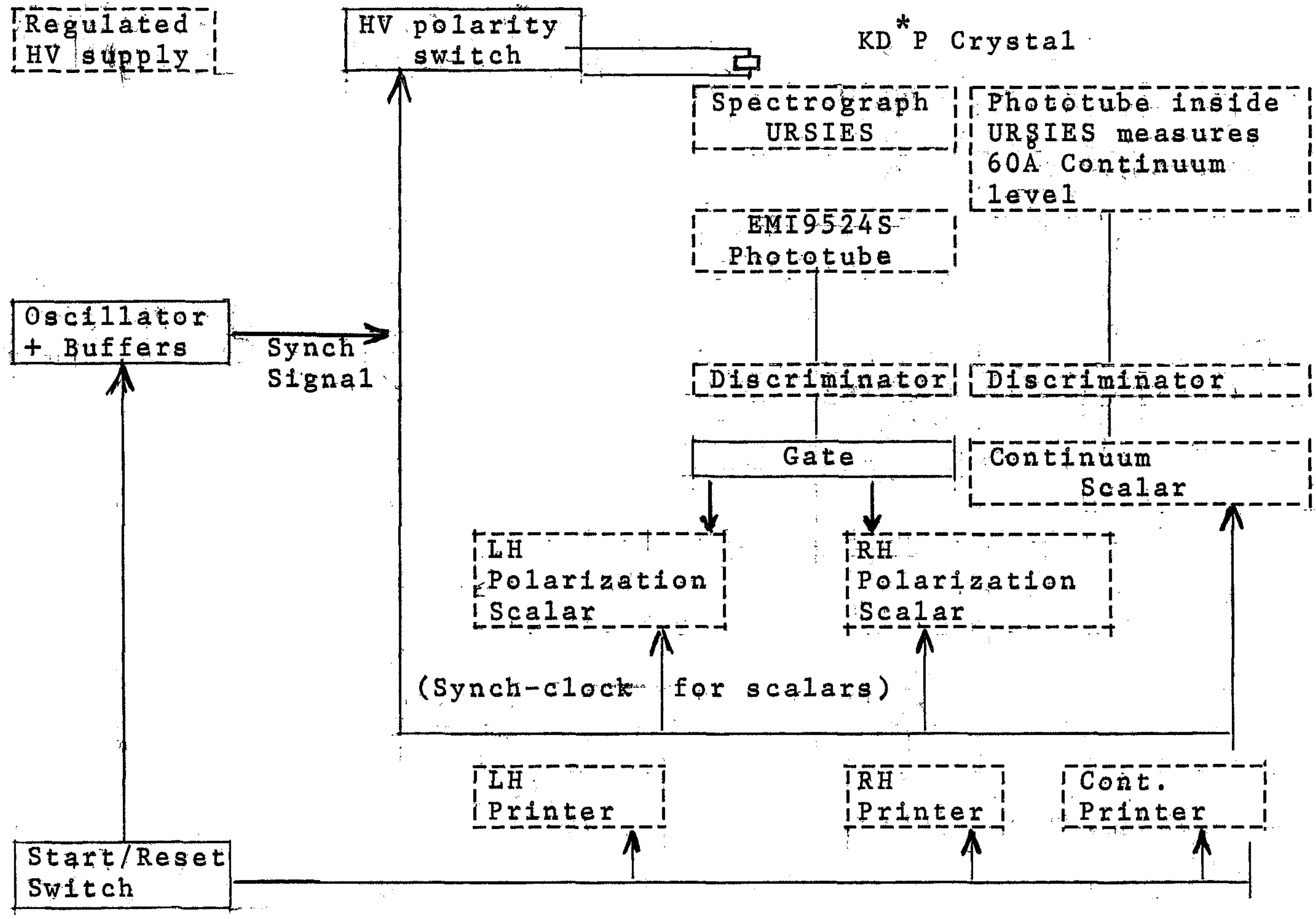
The major instrumental development this period has been the construction of the oscillating magnetometer assembly. This has to a great extent been accomplished by one of our graduate students, Harry Peterson, (B.S. from Cal. Tech.)

who has become increasingly involved in the work of our Astrophysics Group.

Last year in the first crude version of the magnetometer the high voltage was manually switched from negative to positive voltage. As pointed out by Severny (private communication, 1970) a single slit system like ours, has even more stringent demands than the conventional two or three slit magnetometer systems on a chopping mode of observation in order to compensate for seeing fluctuations.

Below is a block diagram of the oscillating magnetometer assembly.

Block Diagram of Oscillating Magnetometer Assembly



The high voltage oscillator modulates the KDP plate with a 100 HZ square wave and conditions the KDP plate to alternately sample the right hand, σ_R, and the left hand, σ_L, circularly polarized light components of the NaD lines at a given wavelength in the wings. The outputs in these two channels is then recorded in two separate systems of counters and printers.

A very versatile dual channel photon counter has been acquired which, in a single unit, combines the functions of our previous two counter systems. The multifunctional, high speed photon counter produced by SSR Instruments Co. in consultation with Dr. Dennison of the Mt. Wilson and Palomar Observatories appears eminently suited to our magnetometer needs. This is a dual channel counter which can be programmed to display and print out a difference count between the two channels, as well as the sum of the two channel counts. In the former mode the dark and the scattered light contributions are automatically eliminated and a pure Zeeman difference signal is recorded, $\Delta=\sigma_R-\sigma_L$. This signal we record as a function of wavelength with our grating or pressure scanning modes of operation. The observed variation with wavelength will then be compared with the theoretical predictions of Dr. Yun (see Figures 9a and b). In the case of the NaD line profiles the difference signal is quite small (1-2%) which require utmost precision in the recording technique; such conditions favor the use of pulse counting techniques rather than photographic or dc-strip chart recording techniques. The NaD lines are chosen because different parts of the wings are formed in different atmospheric layers so that ultimately, information on the magnetic field gradients as a function of optical depth should be forthcoming.

Unfortunately, the continuation of inclement weather, low solar activity (lack of sunspots) and instrumental malfunctioning (grating screw stuck) has prevented us from obtaining any spot scans of the NaD_2 Zeeman components.

However, on April 20 of this year, we did obtain a test scan of the CrI λ4254 line in a sunspot. The results are displayed in Figure 5. The ordinate is the difference signal $\Delta=\sigma_R-\sigma_L$, and the abscissa is the wavelength. The expected switch-over effect from positive to negative value as one goes through the linecenter is clearly demonstrated.

This corresponds to the fact that on one side of the line center, one type of circular polarization will have a higher intensity than the other, with the reverse situation being the case on the other side of the line profile. During the coming research period we naturally anticipate to obtain fullfledged scans of the NaD - Zeeman profiles.

In this period we will also look into the modification of the present magnetometer to make it a 4-Stokes parameter sampler. It is fairly trivial to build in a 0 to $\lambda/2$ retardation in the KDP plate in order also to measure the linear polarization component of the magnetometer. The idea is to incorporate these retardations into the present sampling cycle in the chopping mode, provided it requires no change in the relative orientation of the KDP-plate and the polarizer. This is possible for the 2-slit magnetometer (Beckers 1968) but has not yet been investigated for a single slit magnetometer such as ours.

II. Theoretical Studies of Sunspots

Most of our theoretical efforts have been placed on an attempt to generate complete profiles of ~~the~~ Zeeman components of a magnetically sensitive line. In conjunction with recent improvements on the theory of line formation in a magnetic field along with the observational techniques, it becomes of great interest to make an extensive investigation on the magnetic properties of sunspots, which have not been studied in great detail.

Last year we proposed a new model atmosphere of a large sized umbra (i.e., umbral area, $A_u \approx 100$) based on our photoelectric observations. It has been shown that our proposed model not only accounts for the recent continuum observations (e.g., Rödberg (1969) and Wittmann and Schröter (1969)) but also for the profiles of the observed NaD_2 line (Fay, Wyller and Yun (1970)).

During the present research period we have conducted an additional test regarding the quality of our model by calculating the absolute emergent intensities at various wavelengths ranging from 4000Å to 14,000Å. Figure 6 presents the distribution of the computed intensities along with a comparison of the observations made by Wöhl, Wittmann and Schröter (1970). In addition, a few leading umbral models (i.e., Stellmacher and Wiehr (1970) and Henoux (1969)) are also included in the comparison. As noted from the figure, our model represents the observations satisfactorily, lying within the range of observational uncertainty. Various lines of evidence tested so far seem to corroborate the relevance of our new model to the atmosphere of a large sunspot umbra, thus leading to a conclusion that our umbral model can be safely utilized in a study of the magnetic structure in a sunspot with the help of our forthcoming magnetic observations.

In the last few years the theory of line formation in a magnetic field has been greatly improved by several workers. Moe (1968) introduced a new method of solving Unno's radiative transfer equations without any special assumptions regarding the model atmosphere except for a restriction of a homogeneous magnetic field. Staude (1969), Beckers (1969 a,b) and Rees (1970) further generalized this problem to treat the case in which the magnetic field may vary with depths. Accordingly, it becomes more desirable to have a realistic, refined sunspot model in order to capitalize on the improvement of the theory of line formation. Up to the present a number of umbral models have been proposed but without any estimate of the field variation. Only a few workers (e.g., Deinzer (1965) and Yun (1968)) have attempted to carry out some computations of the magnetic field in the interior of a spot as a self-consistent solution of the problem, and virtually no efforts have been made to consider theoretically the field in the region where most lines are formed.

Accordingly, we have attempted to calculate the field strength in the atmosphere of a typical sunspot umbra, making use of the magnetostatic theory of sunspots developed by Schlüter and Temesvary (1958) together with the use of our umbral model. According to the theory (see details by Yun (1970)), the following four parameters are required to be specified: (1) surface magnetic field strength, B_o (2) its vertical field gradient (3) total magnetic flux, Φ passing through a sunspot under consideration, and (4) angle of inclination of a line of force, θ_p at the outer edge of the penumbra, describing the "fanning out" of the lines of force in the spot. In the present study we define the "surface" of the spot at a geometric depth, Z_D, measured inward from a level of the normal photosphere corresponding to an optical depth, say, $\tau_o=0.4$ to that of the same optical depth $\tau_o^*=0.4$ in the spot (i.e., the "Wilson depression"). The depression has been taken $Z_D=650$ Km in accordance with a recent estimate by Wittmann and Schröter (1969). The values of the angle of inclination, the surface field strength and the total magnetic flux have been selected $\theta_p=76^o$, $B_o(Z_D) = 2930$ gauss and $\phi = 1.53\times10^{22}$ gauss cm^2 respectively, following our earlier investigation (Yun (1970)). Because of the diversity of observed values cited in the literature for the vertical field gradient, three values, 0.5, 1.0 and 2.0 gauss/km, have been considered in the present calculation.

The results of the calculation are presented in Figure 7, where the abscissa represents the logarithmic optical depth of the umbra at 5000Å, τ_0^*, and the ordinate is the computed field strength in gaussian units. As can be seen from the figure, the computed field strength increases linearly with the logarithmic optical depth, regardless of the selected values of the surface field gradient. The existence of the linearity between the field strength and the logarithmic optical depth is noteworthy and it will undoubtedly simplify the problem in analyzing our magnetic observations and furthermore, in constructing an empirical magnetic model based on the observations. It is also interesting to note that the computed strength of the field in the upper layers still remains fairly large, corroborating the observations made by Severny and Bumba (1958), who have shown that the spot magnetic field penetrates well into the chromosphere.

Our effort has continued to develop a computer program to generate complete profiles of magnetically active lines. At the present time our program is in operation under the simple Unno's solution (1956). The Unno's solution will soon be replaced by a direct numerical solution of the transfer equations so as to treat the most general cases.

For the purpose of testing our computer program at the present stage of development, one of the most frequently studied lines, FeIλ5250.2, has been considered, using a model of the normal photosphere and assuming a homogeneous magnetic field of 2400 gauss. The resulting computed profiles are shown in Figure 8a, and 8b, where the quantity γ refers to the angle of inclination of the magnetic field vector to the line of sight. Figure 6c and 6d are the same profiles as observed through a quarter-wave analyzer. These results are found compatible with those of Moe (1968), which have been computed by means of his own new technique of solving the transfer equations.

A similar calculation has been employed to the NaD_1 and D_2 lines, using our umbral model. The difference Δ between the right and left-hand circularly polarized components (normalized by the continuum) has been evaluated at each given wavelength within the NaD lines. The results are shown in Figure 9a and 9b, indicating that only a few percent of the intensity difference between the two polarized components is expected. On the other hand, FeI5250.2 line yields a substantial amount of polarizations as illustrated in Figure 9c and 9d. However, it should be pointed out these numerical values cited in our discussion have been based on the <u>simple</u> Unno solution. Further elaborate calculations by a direct numerical integration of the transfer equations will warrant reliable figures for the present problem.

Colloquia and visits to other observatories:

1. Colloquium on URSIES given at Osservatorio Astrofisico di Arcetri, Firenze, Italy, June 18, 1971. Discussions with Dr. A. Righini on their building and analogue to URSIES.
2. Visit of June 21, 1971 to Solar Field Station of Gottingen University at Locarno, Switzerland and discussions with Drs. Wittman and Rossbach on Sunspot photoelectric magnetometer observations.
3. Visit June 22, 1971 to Solar Field Station of Oxford University at Gornergrat, Switzerland and discussion with Dr. A. Petford on their experience in interfacing a PDP-8 computer with their solar spectrograph.
4. Visit August 30 to Brorfelde Observatory of Copenhagen University and discussion with Professor A. Reiz on their polar siderostat.

Papers published, in press or submitted:

1. Fay, T., Marenin, I. and Van Citters, W., 1971, J. Quant. Spectr. Rad. Transfer, 11, p. 1203, "Perturbation Analysis and Constants for the Red System of the Cyanide Radical."
2. Fay, T. and Wyller, A.A., 1971, Proceedings of I.A.U. Symposium no. 43 on Solar Magnetic Fields, Paris, August 31 - September 4, 1970, p. 60, "A Pressure-Scanning Fabry-Perot Magnetometer."

3. Yun, H.S., 1971, Solar Physics, 16, 379
"A New Empirical Model of a Sunspot Umbra".

4. Yun, H.S., 1971, Solar Physics, 16, 398
"A Magnetostatic Sunspot Model with 'Twisted' Field"

5. Yun, H.S., 1971, Solar Physics (in press).
"Magnetic Fields in Umbral Atmospheres under Similarity Configuration"

6. Fay. T., Wyller, A.A. and Yun, H.S., submitted to Solar Physics, "Photoelectric Line Profiles in Umbral Spectra"

7. Fay, T. and Wyller, A.A., to be submitted to Applied Optics "URSIES - An Ultravariable Resolution Single Interferometer Echelle Scanner"

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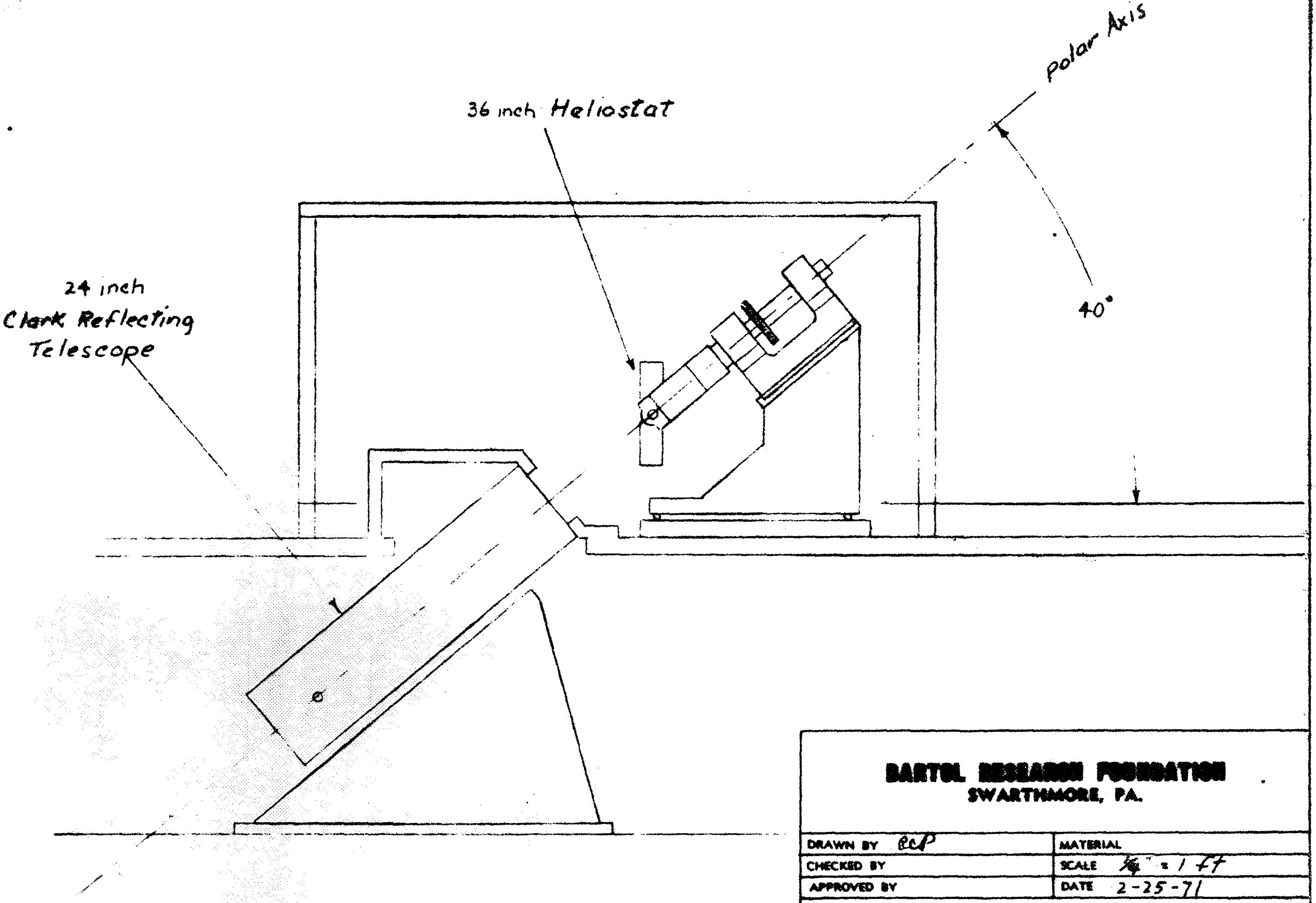


BARTOL RESEARCH FOUNDATION
SWARTHMORE, PA.

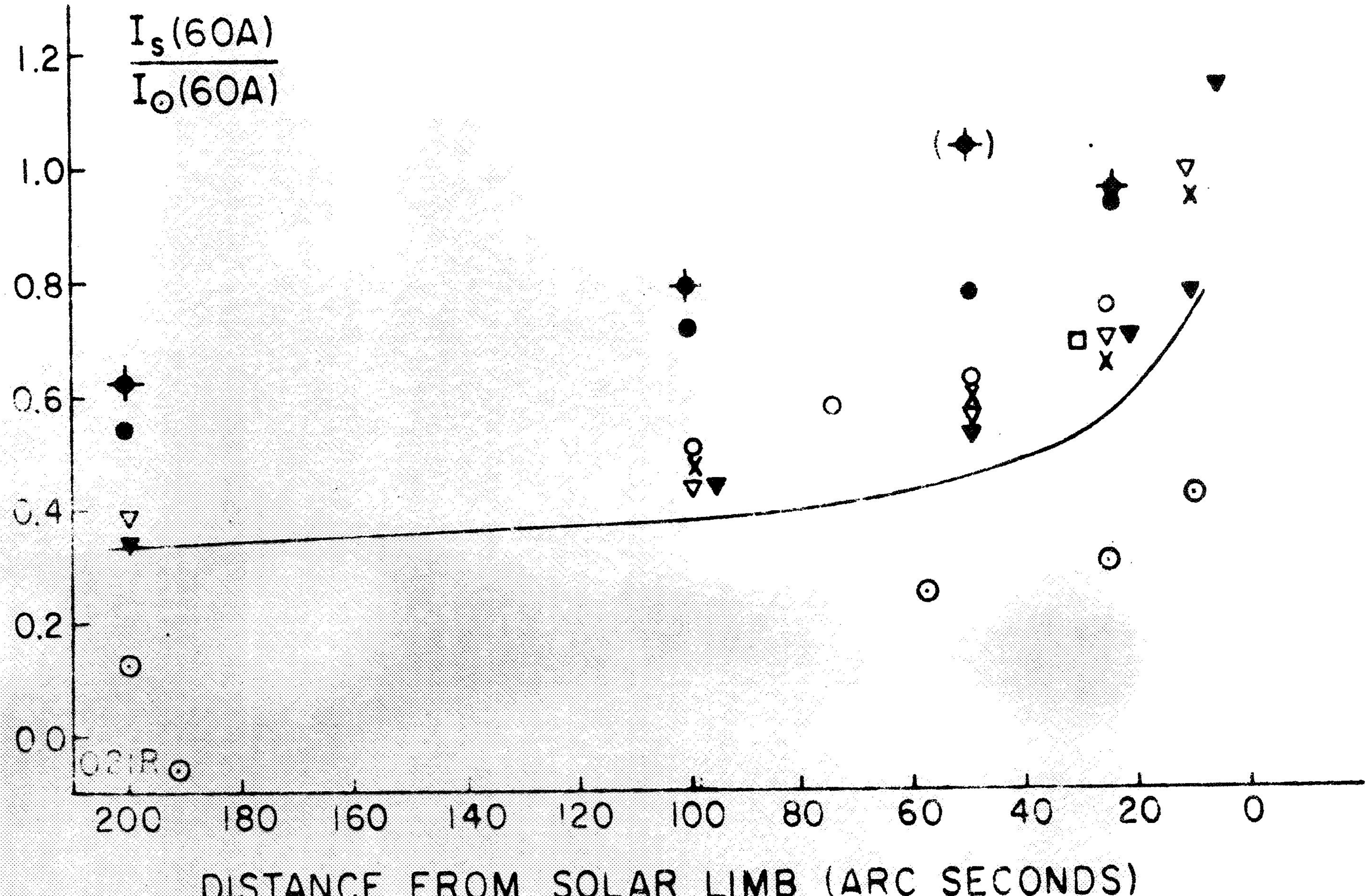
DRAWN BY ecP	MATERIAL
CHECKED BY	SCALE 1/4" = 1 ft
APPROVED BY	DATE 2-25-71

TITLE: Proposed Bartol Telescope

PROJECT	DWG. NO. 6-A-83

TOLERANCES ON MACHINING DIMENSIONS UNLESS OTHERWISE STATED:
FRACTIONAL ± 1/64" DECIMAL ± .005" ANGULAR ± 1/2°

Fig. 1



$\frac{I_s(60A)}{I_\odot(60A)}$
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.2 R
200
180
160
140
120
100
80
60
40
20
0
DISTANCE FROM SOLAR LIMB (ARC SECONDS)

Fig. 2

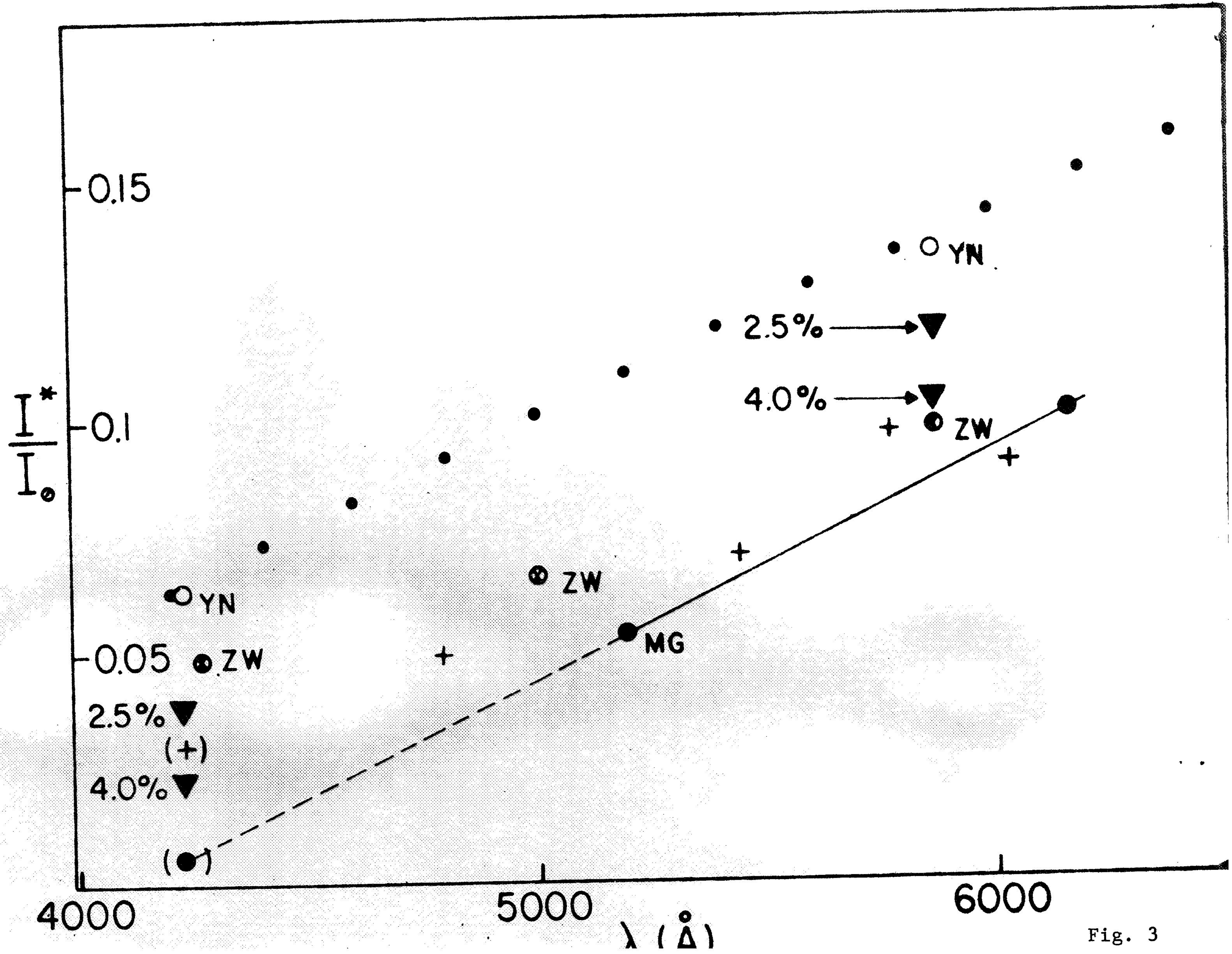

$\frac{I^*}{I_\odot}$
0.15
0.1
0.05
4000
5000
6000
λ (Å)
YN
ZW
2.5%
(+)
4.0%
( )
ZW
MG
2.5%
4.0%
YN
ZW

Fig. 3

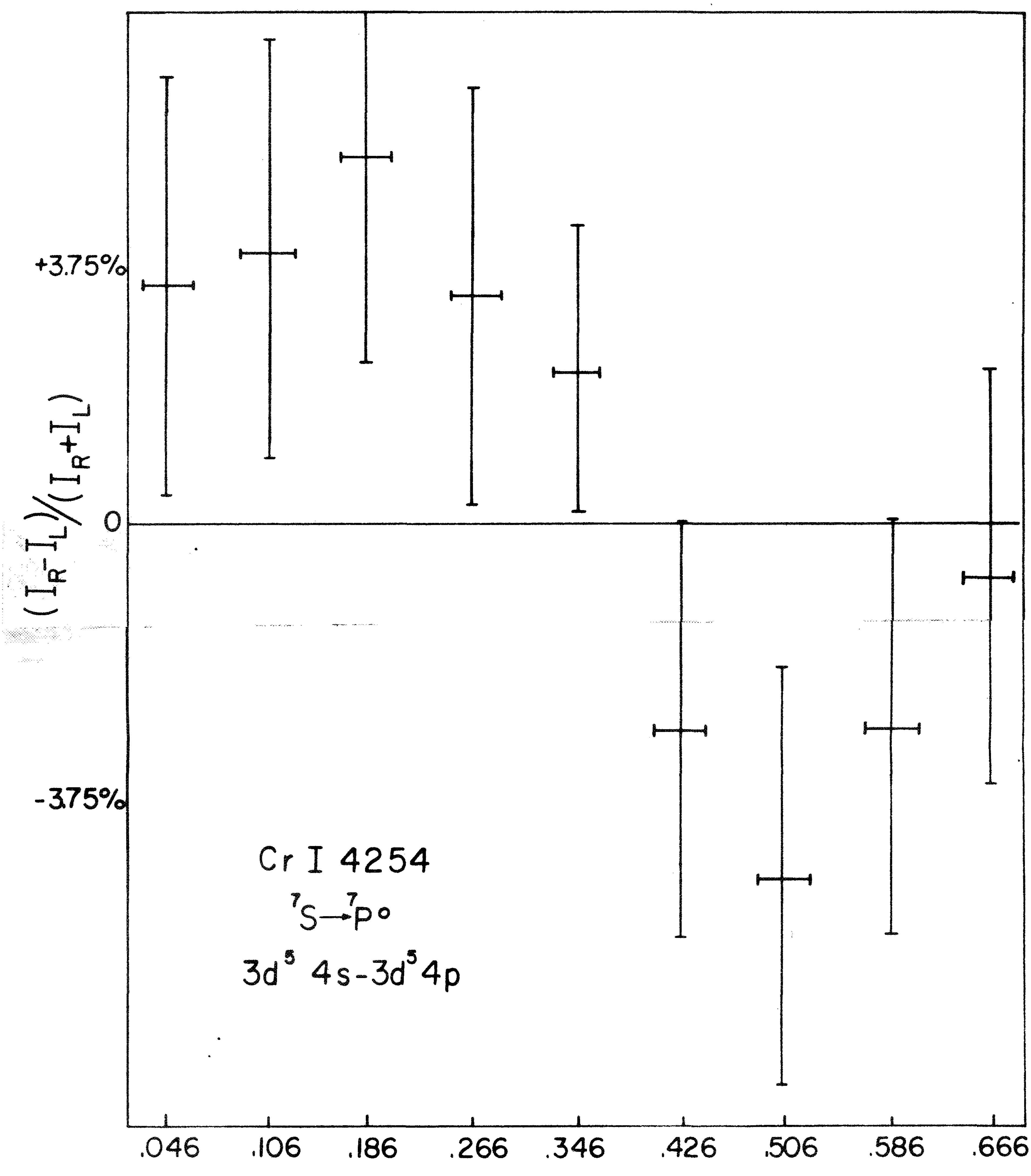

+3.75%
0
-3.75%
$(I_R - I_L)/(I_R + I_L)$
Cr I 4254
$^7S \rightarrow {}^7P^\circ$
$3d^5\ 4s - 3d^5\ 4p$
.046
.106
.186
.266
.346
.426
.506
.586
.666

Fig. 4

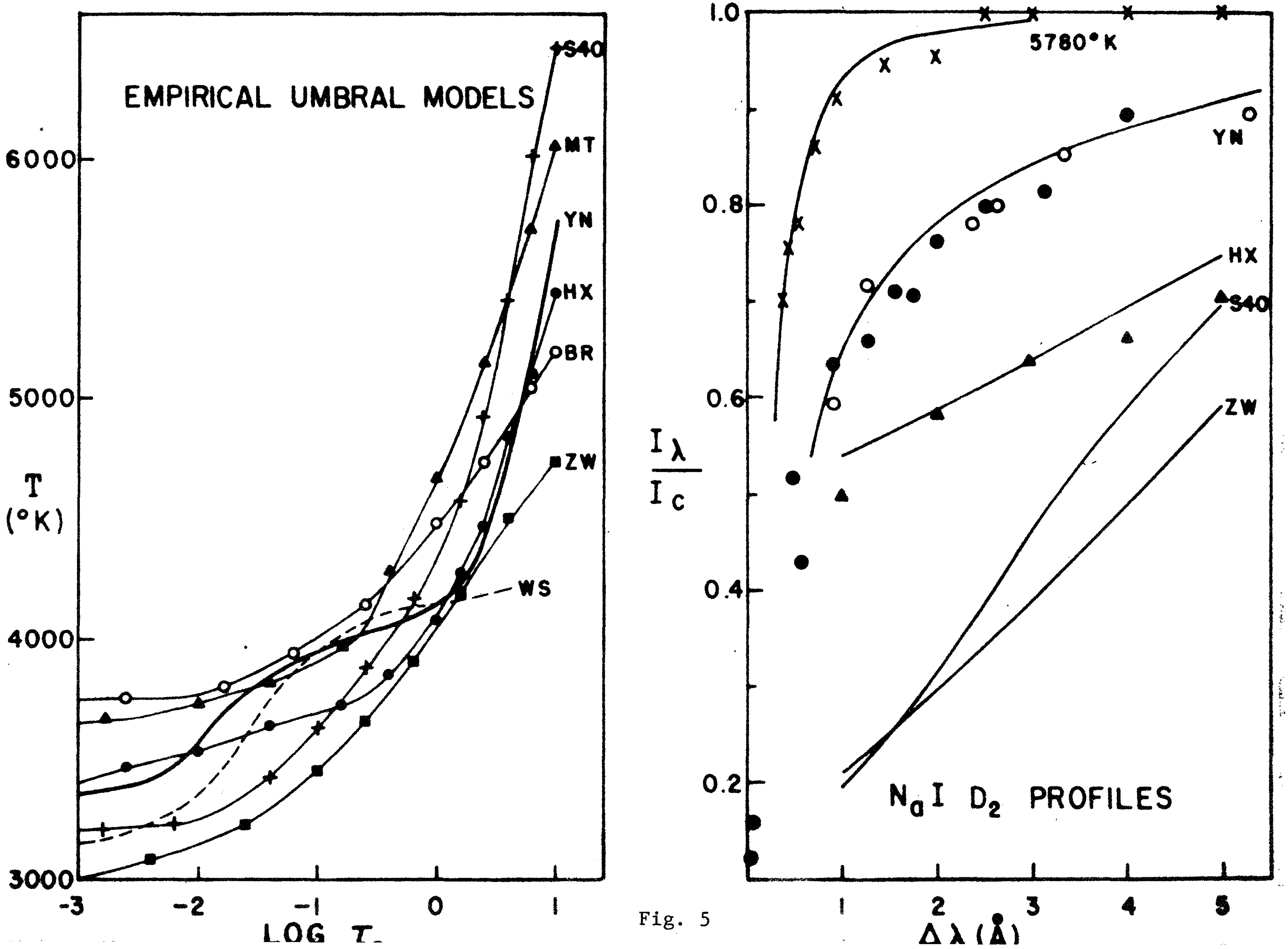

EMPIRICAL UMBRAL MODELS
S40
MT
YN
HX
BR
ZW
WS
T
(°K)
6000
5000
4000
3000
-3
-2
-1
0
1
LOG τ
5780°K
YN
HX
S40
ZW
N_a I D_2 PROFILES
$\frac{I_\lambda}{I_c}$
1.0
0.8
0.6
0.4
0.2
1
2
3
4
5
$\Delta\lambda$ (Å)

Fig. 5

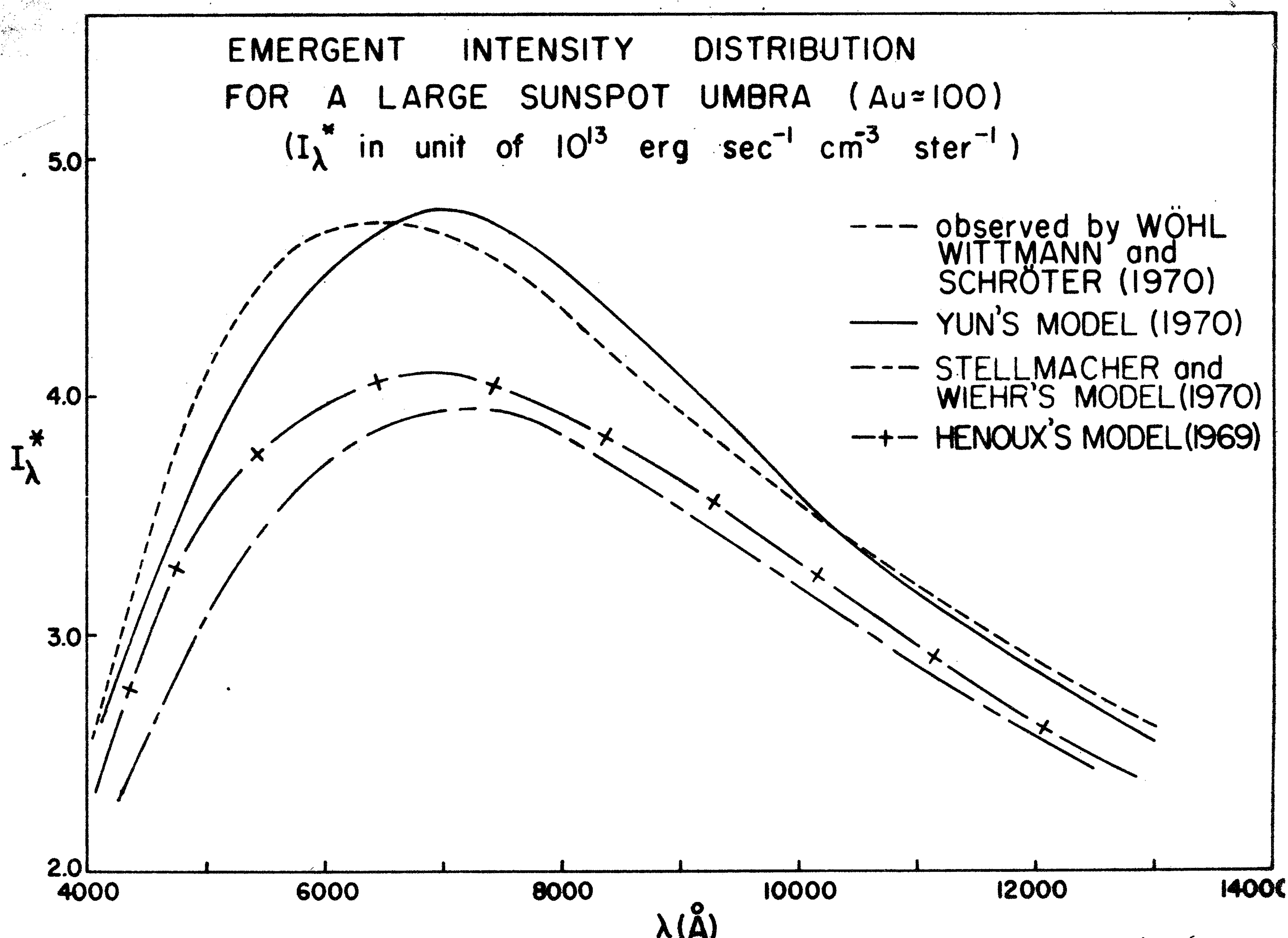

EMERGENT INTENSITY DISTRIBUTION
FOR A LARGE SUNSPOT UMBRA (Au≈100)
(I_λ^* in unit of 10^{13} erg sec^{-1} cm^{-3} $ster^{-1}$)
observed by WÖHL WITTMANN and SCHRÖTER (1970)
YUN'S MODEL (1970)
STELLMACHER and WIEHR'S MODEL (1970)
HENOUX'S MODEL (1969)
I_λ^*
5.0
4.0
3.0
2.0
4000
6000
8000
10000
12000
1400
λ(Å)

Fig. 6.

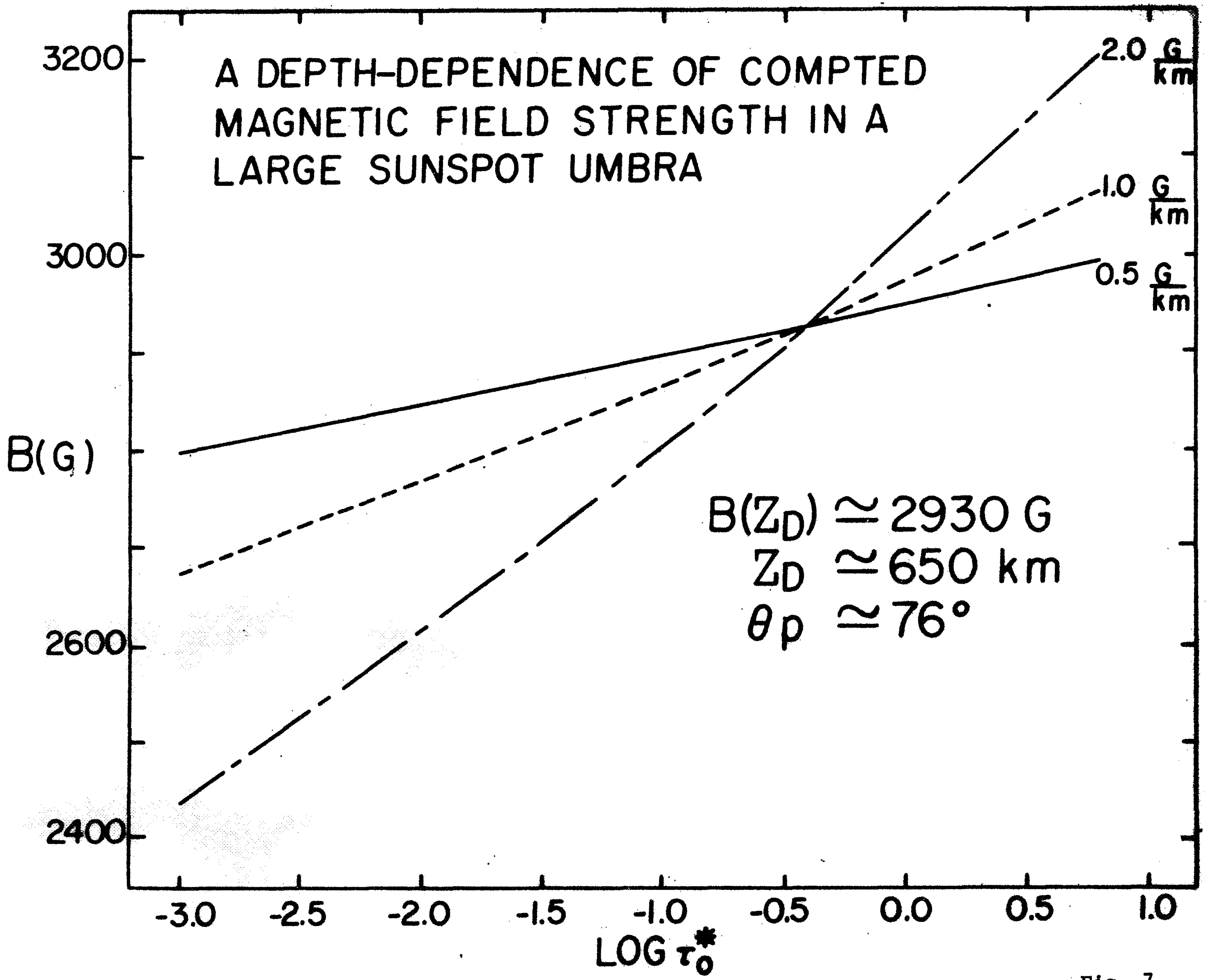

A DEPTH-DEPENDENCE OF COMPTED MAGNETIC FIELD STRENGTH IN A LARGE SUNSPOT UMBRA
2.0 G/km
1.0 G/km
0.5 G/km
B(Z_D) ≃ 2930 G
Z_D ≃ 650 km
θp ≃ 76°
B(G)
3200
3000
2600
2400
-3.0
-2.5
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
LOG τ*₀

Fig. 7

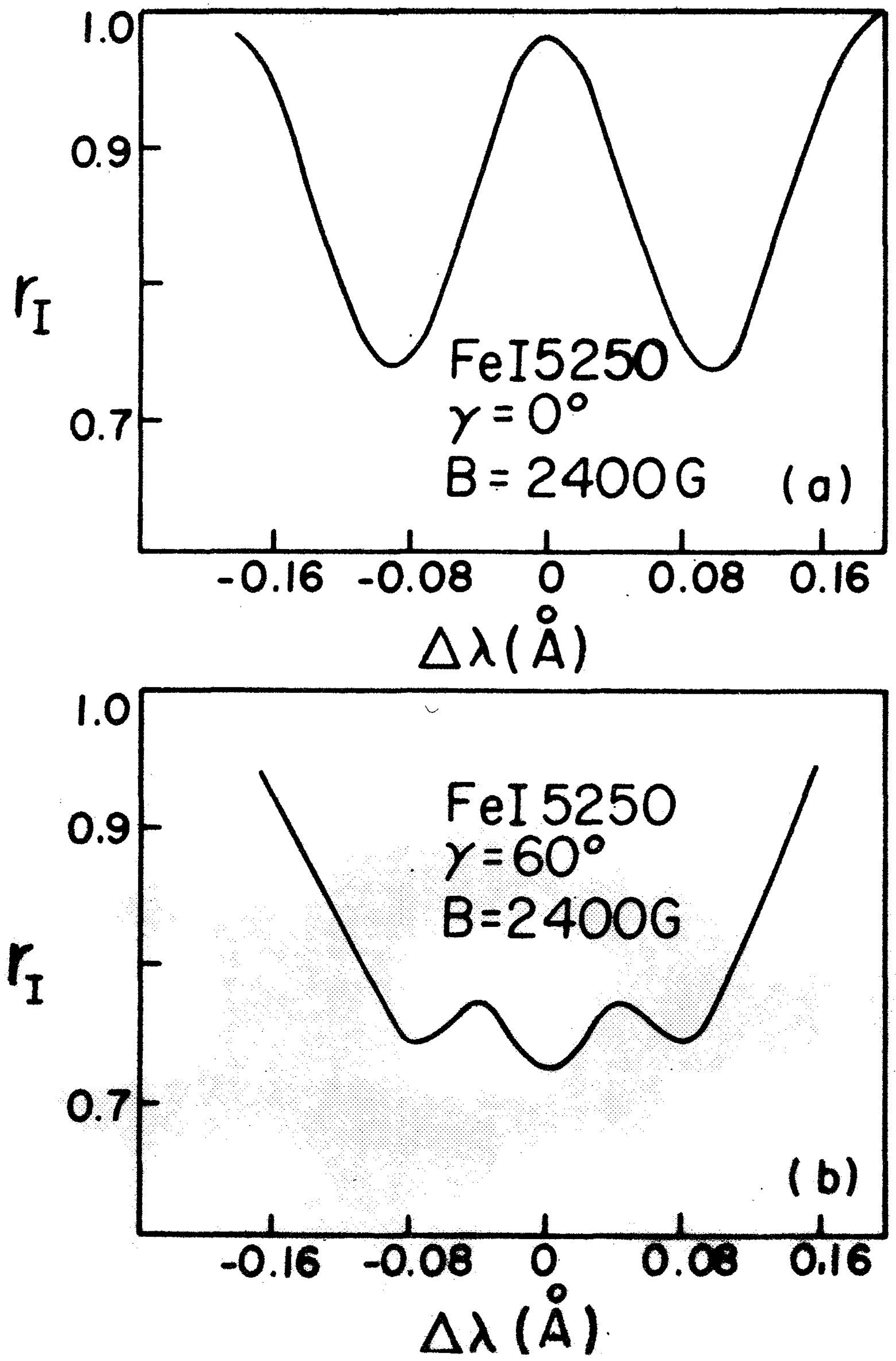


Fig. 8a and 8b

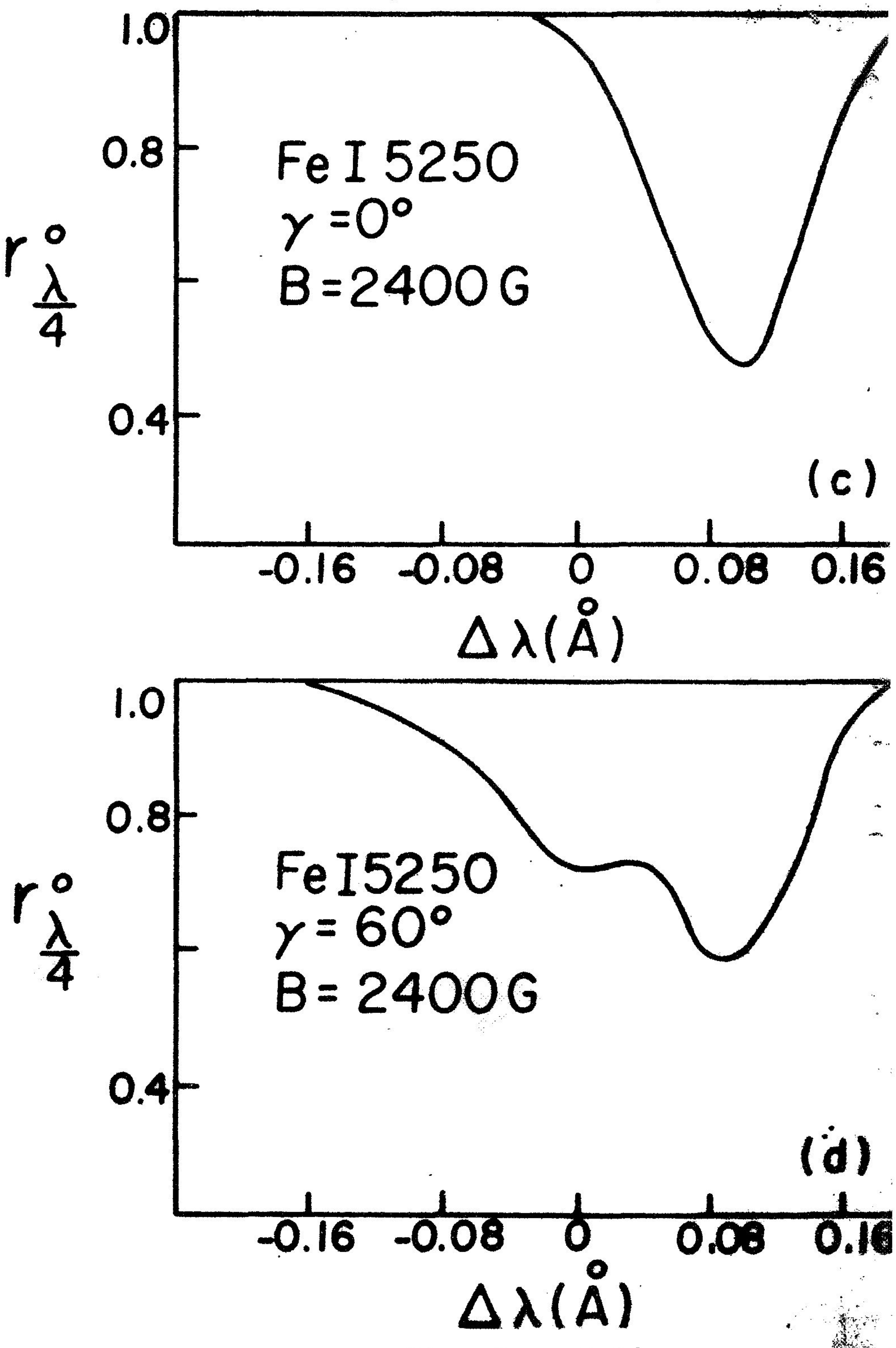


Fig. 8c and 8d

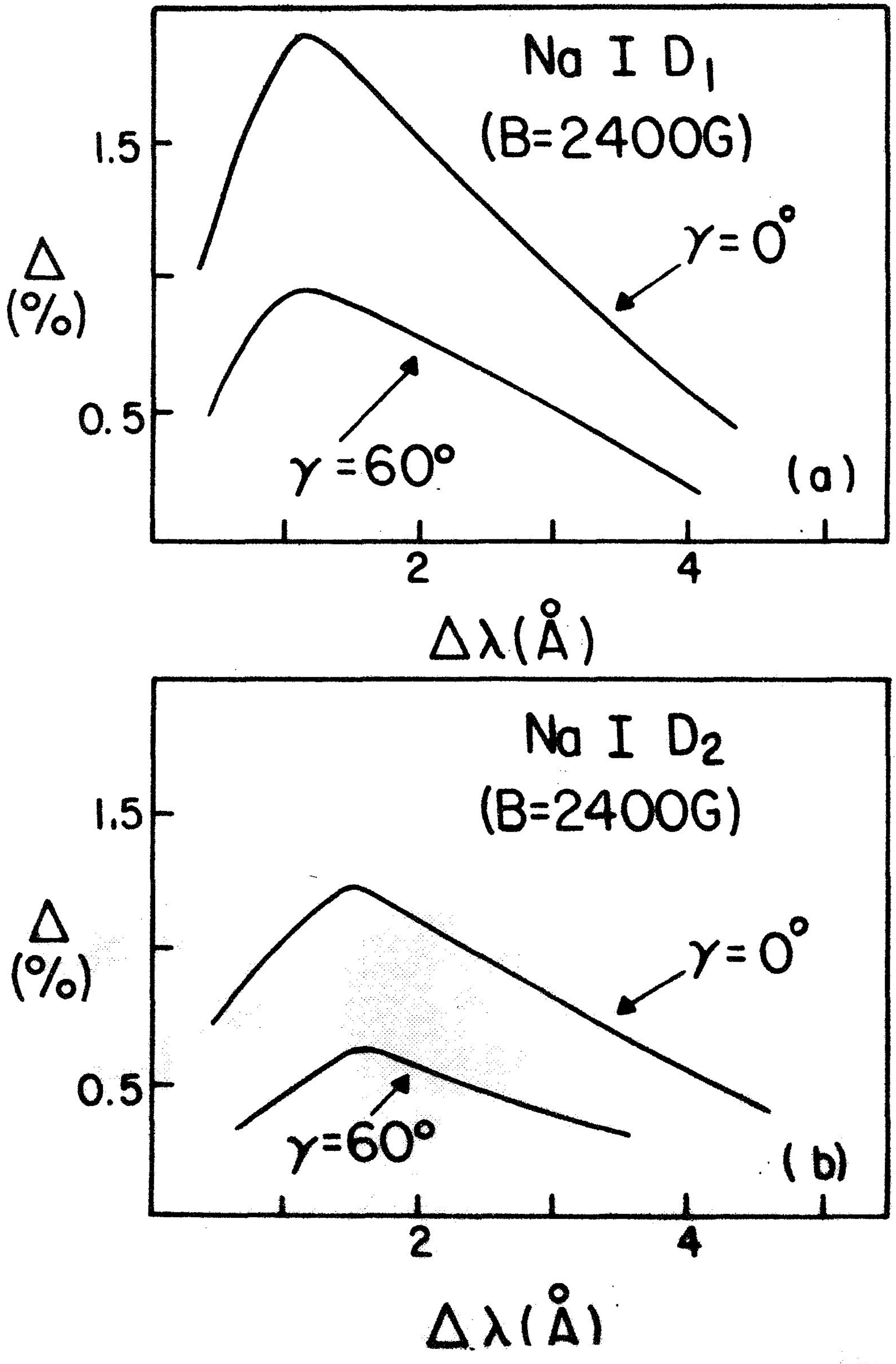


Fig. 9a and 9b

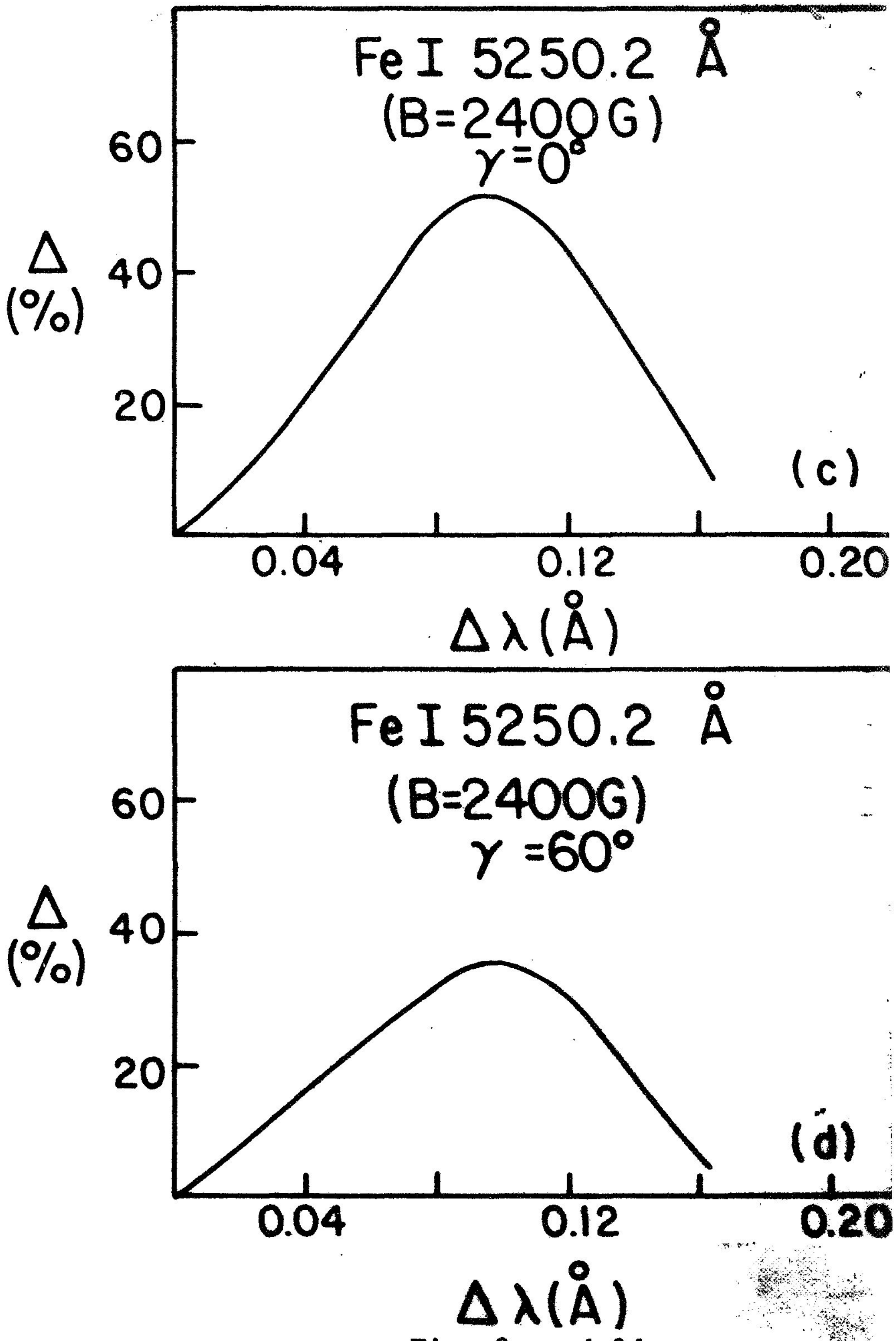


Fig. 9c and 9d