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Measurement of Macroscopic Electric Fields in Solar Plasma Structures

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The work performed in our Phase I effort has led to several important advances in our investigation of a new technique for remote sensing of plasma electric fields. For one, we have been able to place the atomic physics underlying the technique on a firmer basis and verify that the polarization structure of the high Balmer and Paschen lines behaves as predicted by perturbation theory. Second, ~~we have analyzed~~ Balmer- and Paschen-line observations of erupting prominences obtained at Sacramento Peak Observatory and shown that the marked increase in sensitivity of the technique expected with the Paschen lines can be realized. Third, we have improved our understanding of the interpretation of the observed hydrogen-line broadening, and shown that the sensitivity of the technique, when applied to structures emitting intense hydrogen lines, can exceed 10 volts cm^{-1}. This sensitivity is more than adequate to test predictions of transverse electric fields intensities and orientations, in models of flares and other active phenomena. Our goal ~~in Phase~~ II is to construct an instrument optimized for solar plasma electric field measurements, to be installed at

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the SPO Big Dome. We anticipate that such an electrograph would make important advances toward understanding the mechanisms and prediction of solar eruptions such as flares and active filaments.

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I. Summary

The work performed in our Phase I effort has led to several important advances in our investigation of a new technique for remote sensing of plasma electric fields. For one, we have been able to place the atomic physics underlying the technique on a firmer basis and verify that the polarization structure of the high Balmer and Paschen lines behaves as predicted by perturbation theory. Second, we have analyzed Balmer- and Paschen-line observations of erupting prominences obtained at Sacramento Peak Observatory and shown that the marked increase in sensitivity of the technique expected with the Paschen lines can be realized. Third, we have improved our understanding of the interpretation of the observed hydrogen-line broadening, and shown that the sensitivity of the technique, when applied to structures emitting intense hydrogen lines, can exceed 10 volts cm^{-1}. This sensitivity is more than adequate to test predictions of transverse electric fields intensities and orientations, in models of flares and other active phenomena. Our goal in Phase II is to construct an instrument optimized for solar plasma electric field measurements, to be installed at the SPO Big Dome. We anticipate that such an electrograph would make important advances toward understanding the mechanisms and prediction of solar eruptions such as flares and active filaments.

II. Technical Objectives

i) To carry out a concerted program of observations at the SPO Big Dome, using the polarization-dependence of Balmer-line Stark broadening as a diagnostic technique, to investigate possible macroscopic electric fields in chromospheric spicules. Also, to continue our ongoing program using this technique to study the behavior of macroscopic E-fields in flares, post-flare coronal loops, and eruptive prominences.

ii) To analyze existing SPO spectra and obtain new observations investigating the extension of this E-field diagnostic technique to the near infrared high Paschen lines emitted by these structures. Thus to take advantage of the increased sensitivity offered by the quadratic increase with wavelength of linear Stark splitting in hydrogen.

iii) To make measurements with this technique in a controlled laboratory environment by obtaining plane-polarized spectra of the Balmer and Paschen lines emitted by a mirror confinement plasma fusion machine under conditions similar to those in coronal loops. Thus to identify improvements in the instrumentation and procedures that could increase the sensitivity and calibration accuracy of the solar observations.

iv) To compare the results of our solar observations and laboratory measurements with theoretical predictions of static and wave-associated electric fields involved in reconnection, particle acceleration, and other non-thermal heating processes in coronal and chromospheric structures.

III Work Performed - Procedures and Results

a) One of the main objectives in Phase I was to seek improvement in the sensitivity of our technique of electric field measurement. Our earlier work (Foukal, Miller and Gilliam 1983, Foukal, Hoyt and Gilliam 1986) indicated that a sensitivity of approximately 75-100 volts cm^{-1} might be achieved using the high Balmer lines.

Improved sensitivity might be expected through observation of the high Paschen lines, since the linear Stark displacement of the hydrogen line components scales as λ^2 for a line of given upper quantum number. This indicates that the high Paschen lines should exhibit roughly 5 times the Stark broadening of the corresponding Balmer lines.

Observations of coronal features emitting strongly in the high Paschen lines are fairly rare, but one case, pointed out to us by L. Gilliam, was the eruptive prominence of 30 April 1974 observed at the SPO USG. The P.I. and CRI staff scientist Ruel Little travelled to Sac Peak in early June, 1987, and during a thorough examination of the USG archives, excellent spectra of a second eruptive prominence (of April 24, 1971) were located.

The high Balmer and Paschen line spectra of these two events were reduced using a PDS microdensitometer at American Science and Engineering. Several scans were reduced in each spectrum and the emulsion noise was further smoothed with a gaussian filter. The intensities of the MgI triplet lines near

3830A and of the SrII 4078 line, whose intensity ratio is density-sensitive, (Landman 1984) were also measured.

A more detailed description of the procedures and results of this analysis is given in our paper, recently accepted for publication by Solar Physics, and included here as Appendix A. The observational findings of most direct interest were that the Paschen lines provide both a significantly more sensitive and more accurate indicator of electric fields in structures with very bright hydrogen lines, than do the high Balmer lines.

Although the intensity of the Balmer lines is greater, so their widths can be measured with greater precision, this advantage is more than compensated by the very high sensitivity of the Paschen lines, described above. Specifically, it can be seen in Fig 1b that discrimination of electric fields at the level of 10 volt cm^{-1} (i.e. the difference between 12 volt cm^{-1} and 22 volt cm^{-1}) is relatively easily achieved with the data for the April 24, 1971 event.

The reason for the higher accuracy achieved with the Paschen lines can be seen from Fig 2. The Stark broadening of the high hydrogen lines causes their wings to overlap and eventually the lines blend (The Inglis-Teller effect). This overlapping makes the electric field derived in the highest series members an upper limit to the true electric field. This is a serious source of absolute error when the high Balmer lines are used, but the error can be neglected for the highest measurable Paschen lines in Fig 2a, because their spacing is greater relative to their width.

In the analysis of the two eruptive prominences we were able to show that the total electric fields, most sensitively and accurately derived from Paschen lines, agreed to within 5-10 volt cm^{-1} with the pressure broadening fields expected at the local electron densities estimated in these prominences from the MgI/ SrII line ratio diagnostic. This result agreed with our previous finding (Foukal, Hoyt and Gilliam 1986) that the total electric fields in bright eruptive prominences are significantly lower than those measured in post-flare loops.

In that previous paper, we had found evidence for electric fields of order 100 volts cm^{-1} in a very bright post-flare loop. However, we realized later that the manner in which the data had been plotted in that paper left it somewhat unclear whether the different slopes seen in the curves of increasing Balmer line width with upper quantum number were caused by differences in the

Stark effect with polarization at the highest Balmer lines, as was concluded there. Instead the differences in the parabolic curve slope at the high Balmer lines might have been caused by differences in optical depth of the lower Balmer lines as observed in the different polarizations.

To remove this ambiguity we replotted the line widths at high and low Balmer numbers separately using both linear and quadratic fits. The results are that the slope behavior was not significantly changed whether the data at high and low Balmer numbers were plotted separately or together. This result further strengthens the evidence for detection of a relatively strong field in the post-flare loops.

b) A second objective in the Phase I program was to determine whether our polarization discriminant could be used to study electric fields in chromospheric structures at the limb and on the disc. A particular aim was to apply it to the Paschen lines observed at the limb. During our visit to SPO in June, the PI and R. Little worked with L. Gilliam to optimize procedures and settings at the coronograph to obtain good spectra of both the high Balmer and Paschen lines from the limb chromosphere. Examination of some archival USG spectra on the disc convinced us that with the possible exception of unusually dark post-flare loops, the contrast of disc structures in the high Balmer lines is unlikely to be sufficient to permit their observation using this technique.

Limb spectra were obtained by L. Gilliam on several occasions during the period June-October 1987. The high Paschen lines were not observed, although we learned recently from L. Gilliam that intense high Balmer lines are seen on some of the spectra. Unfortunately, we did not have this information in time to reduce these spectra during Phase I of this program. Continuing efforts are being made by L. Gilliam to obtain chromospheric limb spectra under conditions of sufficiently good sky transmission and seeing (and also occulting disc adjustment in the infrared) to bring out the Paschen lines.

We found from the literature that strong chromospheric Paschen line spectra were observed during the 1952 eclipse by the HAO expedition (Athay et al.1953). We obtained some of the original plates from G. Athay, and reduced them on the PDS microdensitometer using characteristic curves given in his PhD thesis. Calibrations were available for the Balmer lines, but none were located for the Paschen lines whose analysis was the main object of the reduction. Nevertheless, the analysis was useful in demonstrating the superb signal to noise ratio that could be achieved in eclipse spectra of the chromosphere at the Paschen lines beyond P20.

This result and also the Balmer line results from the same eclipse reported by Redman and Suemoto (1954) have prompted us to investigate the possibility of observations optimized for chromospheric electric field measurement at the 1991 solar eclipse.

c) Spectrometer measurements of the high Balmer lines emitted from a magnetically confined plasma were carried out in part to investigate our polarization discrimination technique in electric fields that were expected to be better known than those in the solar atmosphere. A second aim was to determine whether the technique might be viable as a diagnostic of electric fields in fusion machines in general.

The P.I. gave a seminar on this technique at the M.I.T. Plasma Fusion Center, and the measurements were carried out at the TARA mirror machine in collaboration with T. Moran and K. Brau of the M.I.T. staff. The TARA plasma temperature, density and magnetic fields are much closer to coronal loop values than those encountered in Tokamaks such as the M.I.T. Alcator C. An appropriate spectrometer with a diode array detector was used, with spectral resolution of about 0.4Å. Measurements were carried out during several runs of the TARA, imaging both the hottest plasmas obtained during the RF heating phase of a TARA duty cycle, and also the recombining plasmas found in the subsequent relaxation.

A plot of the highest Balmer lines observable is shown in Fig 3. These lines, up to B18 and beyond, are quite prominent in the recombining plasma. In the hottest plasma they are badly blended (not shown here) with the lines of iron, titanium, etc. present as impurities in the TARA machine.

The radial fields of order 10-100 V cm^{-1} predicted in the TARA machine are expected to occur during the hot plasma phase. During the recombining phase, the only intense fields expected to be present are near the RF antenna. Plans were made to move the spectrometer to a port from which these fields might be viewed, but this was never achieved since other measurements were required on a high priority basis before the October, 1987 final closing of the TARA machine by DOE.

During our study of the literature during Phase I we found descriptions of Soviet work carried out at theta pinch fusion machines using a technique similar to ours (Berezin et al 1972). This work was performed using only the lowest Balmer lines up to H_γ, since turbulent fields of order kV cm^{-1} in those machines were studied. But the observation of fields agreeing well with theory in this work indicates that the basic technique is valid. The extension of its validity to the higher Balmer lines is based on our investigation of recent results in atomic physics discussed in section (d) below.

Additional experimental work intended to demonstrate the viability of our technique was initiated at Bell Laboratories in the Spring of 1987, before this contract formally began. The PI travelled to Bell Labs in Murray Hill, N.J. to perform measurements with Dr. R. Gottscho using an RF-heated discharge plasma. Preliminary spectra of the high Balmer lines were obtained during these runs, to investigate how much intensity could be expected in lines above B10.

The results indicated that B10 could barely be detected, and laser-induced fluorescence techniques would probably be required to go higher. The field intensities in the discharge were sufficiently high that appreciable Stark effect might be expected even at B8 or B9. However, achievement of improved sensitivity over that recently demonstrated at Bell Labs using a line ratio technique (Moore et al. 1984) would require considerable development work to try out the laser-induced fluorescence techniques.

Continued discussions with Gottscho during this Phase I work indicated that in the present climate of restricted funding at AT&T, additional work would need to be done to determine how electric fields measured with Balmer lines in a hydrogen-rich plasma could be related to the sheath electric fields encountered in molecular plasmas of, e.g., BCL, that are of direct interest in the micro-electronic etching work performed at Bell Labs.

Given the validation of our basic technique provided both by the results of Berezin et al. (1972) and by the recent atomic spectroscopy discussed below, continued emphasis on these laboratory measurements seemed less important than pursuit of the technique's direct application to solar plasmas.

d) Some Important progress was made in validating our basic observational technique and in interpreting the electric fields measured in the solar atmosphere. In the first area, we comprehensively investigated the literature on measurements and interpretation of the hydrogen Stark effect to determine whether the polarization structure of Stark-broadened hydrogen lines predicted by the standard perturbation theory (e.g., Epstein 1916) has been verified in the high lines of the series used in our technique.

We found that the perturbation theory has been amply tested and verified for the lowest members of the Balmer series (see, e.g., Condon and Shortley 1951 and references therein); however, it is difficult to test in the higher lines because they are relatively weak in standard laboratory discharges (as we note above, from our experience in the experiments at Bell Labs).

Discussions with atomic physicists at MIT and Harvard indicated that the perturbation theory was likely to be adequate for our purposes, but that experimental tests had only been made quite recently using laser-induced transitions from the highest Rydberg states of hydrogen to the lower Balmer level. This work (e.g., Delsart et al. 1987, Rothke and Welge 1986) has now shown that the perturbation theory predicts the observed polarization structure of the hydrogen lines to beyond B30 very well, in electric fields spanning the intensity range of interest in solar plasmas.

A second important advance was in the interpretation of the sensitivity of our technique. The calibration of our results so far (e.g., Foukal, Hoyt and Gilliam 1986) relies on matching the observed broadening with increasing Balmer number to that calculated for a given electric field intensity. The widely used tabulation of Balmer-line Stark broadening by Kurochka (1969) parameterizes the line widths by the electron density required to produce the broadening, assuming it is caused by pressure-broadening.

Some confusion has existed in the literature as to the appropriate intensity of macroscopic electric field to assign to a given electron density. A formula for the "mean particle field" given by Griem (Griem 1974, p. 22) had been used by ourselves and by some other authors in this context (e.g., Jordan et al. 1980, Davis 1977). This formula was found to lead to a field intensity estimate about 3.5 times as high, for a given observed broadening, as the classical Holtsmark formula for the electric field expected at a test atom immersed in a medium of a given perturber density. Since the derivation for the mean particle field formula is not given in Griem's book, the difference by such a large factor required investigation.

We found from discussions during Phase I with members of H. Griem's group at the University of Maryland that the Holtsmark formula is definitely the better approximation for determining the homogeneous electric field that would give rise to the observed Stark broadening. In the analysis of Foukal, Little and Gilliam (1987) included here in Appendix A, we then used the Underhill and Waddell (1959) tabulation of the Stark component separations as a function of Holtsmark field, to calculate the true sensitivity of our technique. This analysis showed that the sensitivity of our technique was much higher than the 75-100 volts cm^{-1} that we had earlier felt justified in claiming (e.g., Foukal, Hoyt and Gilliam 1986). As shown by the study of two eruptive prominences in this Phase I investigation, field intensity differences as small as 10 volts cm^{-1} seem to be detectable with observations of the high Paschen lines.

This sensitivity lies well within the range of electric field intensities predicted by recent models of post flare loop (e.g., Kopp and Poletto 1986), of finite resistivity effects on the dynamic of coronal magnetic loops in general (Hinata 1987), and of pre-flare energy build-up associated with eruptive chromospheric filaments. It is also quite adequate for tests of solar energetic partice acceleration processes (see e.g. review by Benz,1987).

IV Summary of Phase I Conclusions and Plans for Phase II Work

The work performed during Phase I has demonstrated that the basic physics underlying our remote sensing technique for plasma electric fields is sound, and that the sensitivity is easily adequate to investigate important problems in solar research. The sensitivity and accuracy of the technique also appears sufficient for application to other areas such as plasma fusion and research on plasma etching techniques. However, our Phase I work showed that its most directly useful and immediate application is to remote sensing of electric fields in the solar atmosphere.

The technique has been implemented so far at SPO with photographic spectra of the high Balmer and Paschen lines, and their reduction to obtain curves of halfwidth against upper quantum number. This technique is similar to early photographic measurements of transverse magnetic fields in sunspots using polarization analyzers and spectrographs. As in the case of the early magnetic measurements this approach has been useful in validating our basic technique, by recording and studying the behavior of a large sample of the high Balmer or Paschen series simultaneously.

However, the fundamental limitation to electric field sensitivity now appears to be set by the noise introduced when spectra at different setting angles of our polarizing prism (now taken several minutes apart) refer to different plasmas due to slow drifts in pointing, and real evolution of the solar structure observed. Significantly improved sensitivity and accuracy (and also essentially real time data acquisition and optimization) could be achieved by constructing an "electrograph" optimized for rapidly obtaining the profiles of one or more of the high Paschen or Balmer lines while the plane of polarization of light admitted to the spectrograph is rapidly changed through several settings.

Our plans for the design and construction of such an electrograph, for its installation at the SPO Big Dome, and for its use during the rising activity phase of solar cycle 22, are set forth in our Phase II proposal. In separate work, we also plan to investigate the possibility of obtaining electric field measurements in the chromosphere during the 1991 eclipse (in Hawaii or in the Yucatan), and in the opportunities offered for an electrograph as a payload on a high altitude balloon launch.

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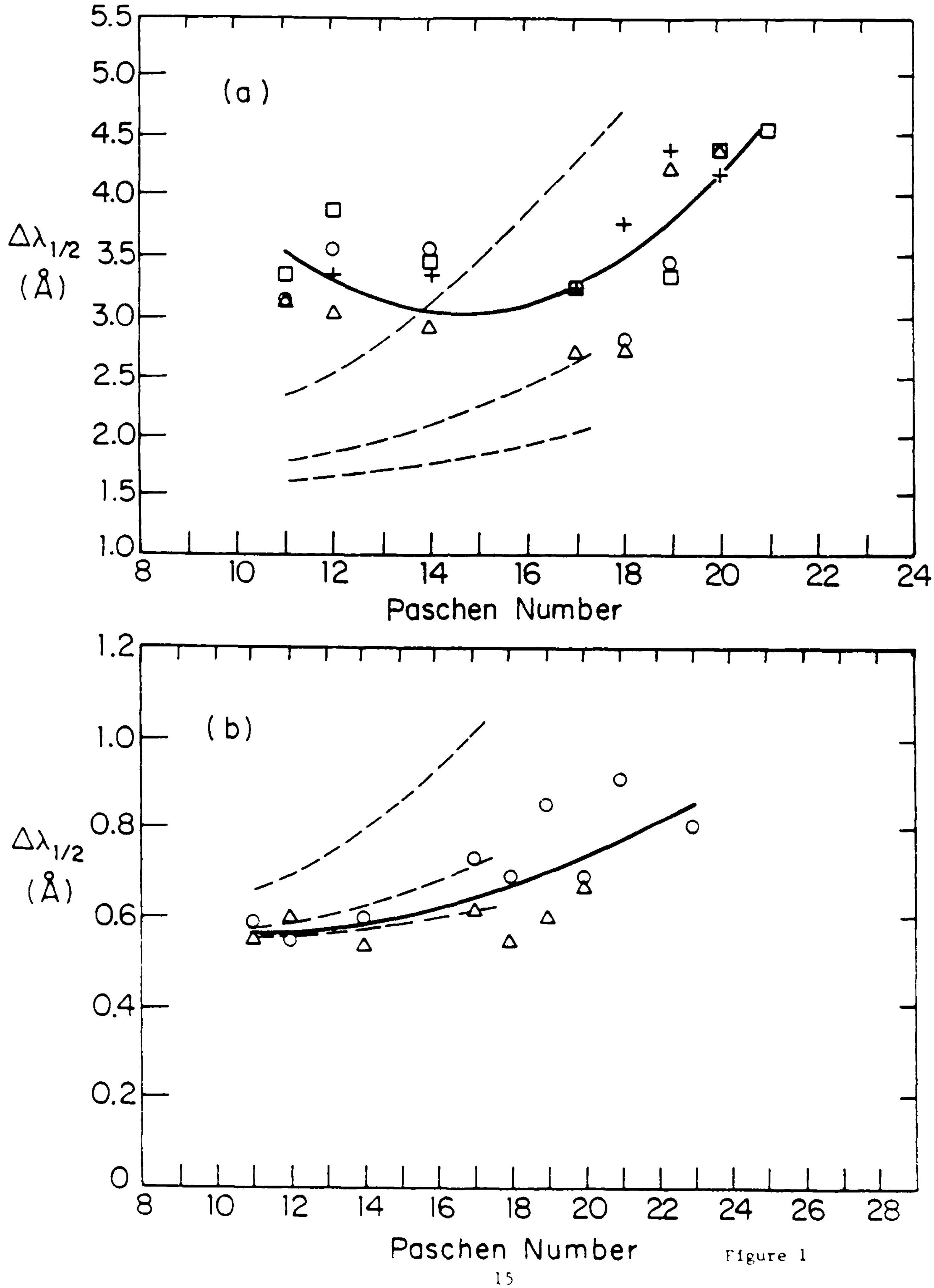
Figure Captions

Fig.1 Plots of $\Delta\lambda 1/2$ against quantum number for the Paschen series in event A (a) and in event B (b). The solid lines represent a least squares quadratic curve fit to the data. Common symbols represent separate microdensitometer scans of the same spectrum. The dashed curves calculated for the Holtzmark field strengths of (bottom to top) 35, 55 and 100 volts cm^{-1} in (a), and 7.5, 12 and 22 volts cm^{-1} in (b).

Fig. 2 Microdensitometer scans with the background subtracted of (a) the high Paschen lines and (b) the high Balmer lines. Instrumental broadening has not yet been removed in the scans shown here.

Fig. 3 Plot of the high Balmer lines (between B12 and B18) measured with a spectrometer and diode array at the TARA mirror machine. Wavelength scale in Angstroms.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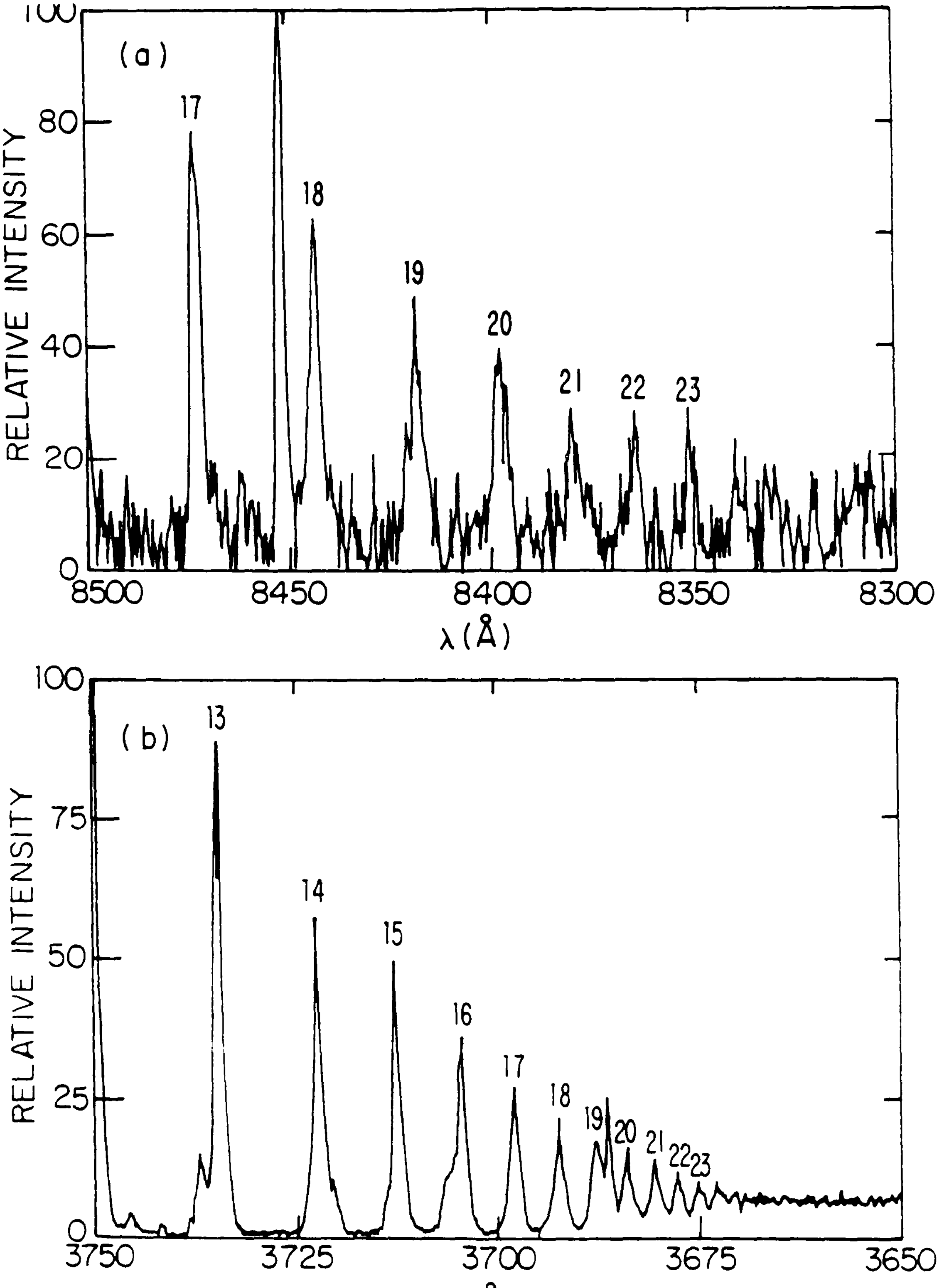
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
(a)
$\Delta\lambda_{1/2}$ (Å)
8
10
12
14
16
18
20
22
24
Paschen Number
1.2
1.0
0.8
0.6
0.4
0.2
0
(b)
$\Delta\lambda_{1/2}$ (Å)
8
10
12
14
16
18
20
22
24
26
28
Paschen Number

Figure 1


(a)
RELATIVE INTENSITY
100
80
60
40
20
0
17
18
19
20
21
22
23
8500
8450
8400
8350
8300
λ (Å)
(b)
RELATIVE INTENSITY
100
75
50
25
0
13
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3650
λ (Å)

Figure 2

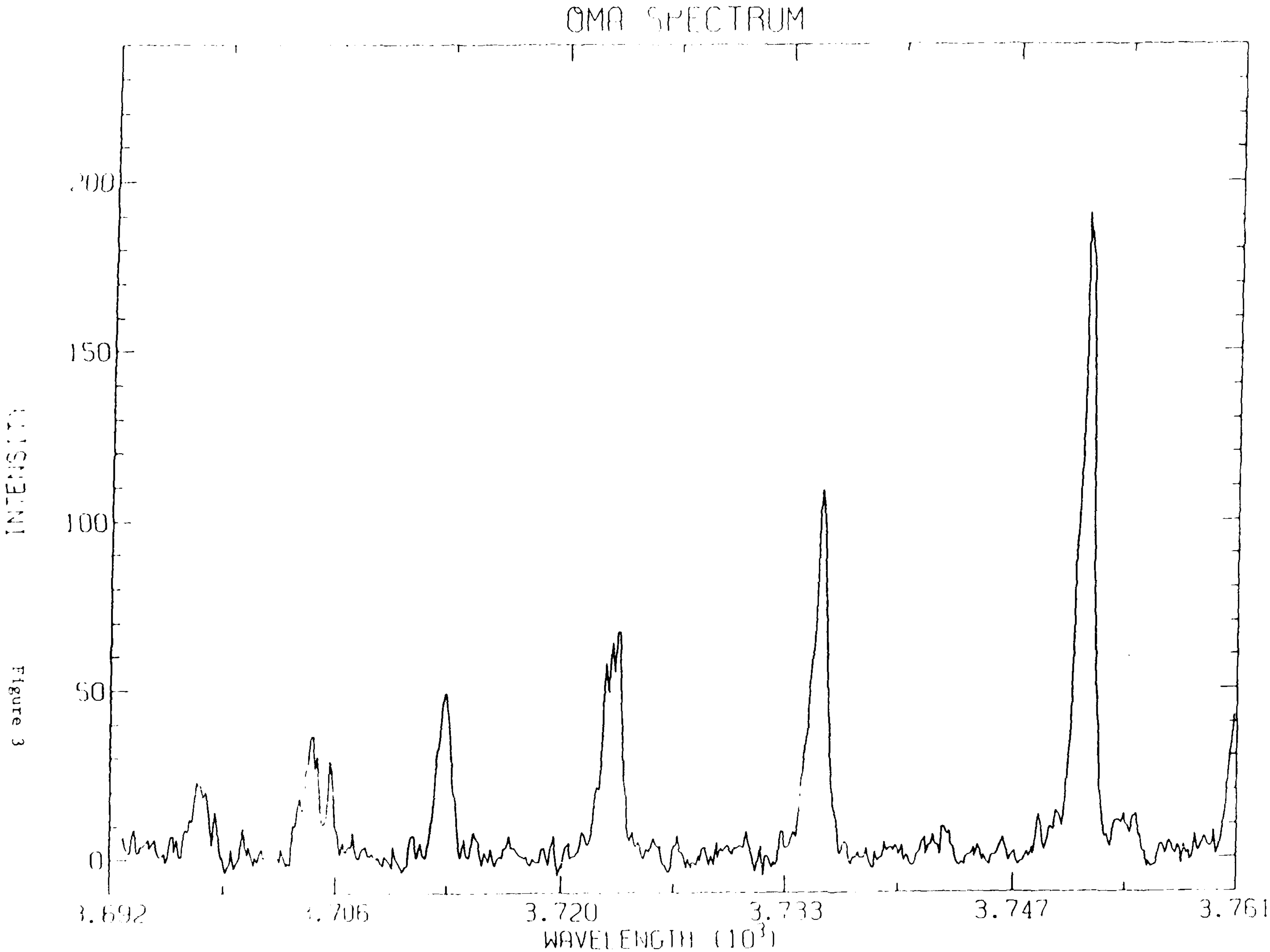
OMA SPECTRUM
INTENSITY
200
150
100
50
0
3.692
3.706
3.720
3.733
3.747
3.761
WAVELENGTH (10³)

Figure 3

SOLA H020

PASCHEN-LINE STARK-BROADENING AS AN ELECTRIC FIELD DIAGNOSTIC IN ERUPTING PROMINENCES

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Abstract. We analyse the Stark broadening of the Balmer and Paschen lines emitted in two bright eruptive prominences, to determine the total electric field in these structures. We show that the Paschen lines provide a significantly more sensitive and accurate electric field indicator than the Balmer lines used previously in such studies. In the two eruptive events analysed here, the total electric fields agree to within 5–10 V cm^{-1} with the pressure-broadening fields expected from local densities of the cool plasma, measured simultaneously and co-spatially by a line-ratio diagnostic. We conclude that in such structures the upper limit to any widespread macroscopic fields is roughly 10 V cm^{-1} or less. This is in agreement with the motional electric field that might be associated with reconnection at the observed rate of the prominences' outward motion of about 135 km s^{-1}.

1. Introduction

Stark-broadening of the high Balmer lines has been commonly used as a diagnostic of local electron density in relatively cool plasmas found in flares (e.g., Švestka and Fritzova-Švestkova, 1967), prominences (e.g., Hirayama, 1963) and the chromosphere (e.g., Feldman and Doschek, 1977). More recently, it has been used to derive the total electric field in post-flare loops and active prominences (Foukal *et al.*, 1983, 1986) to investigate possible macroscopic electric fields associated with reconnection or plasma waves.

In principle, the total electric field should be measurable with significantly improved sensitivity using the high Paschen lines, since the magnitude of the Stark splitting between Balmer and Paschen of the same upper quantum level increases as λ^2 Paschen/λ^2 Balmer (e.g., Condon and Shortley, 1951), thus roughly by a factor 5.3 for high members of the series. The increase in sensitivity actually realized will depend upon the relative importance of Stark effect and other broadening mechanisms such as self-absorption and turbulent Doppler broadening.

Coronal structures emitting intensely in high Paschen lines are quite rare. The bright eruptive prominences of April 30, 1974, and April 24, 1971, offer an interesting opportunity to test this electric field diagnostic, since bright Paschen lines measurable to well beyond P_{20} were emitted during these eruptions. We wish to determine whether evidence for plasma waves or reconnection can be obtained by comparing this total field with the

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microscopic electric field expected from pressure broadening at the plasma density determined by a line ratio diagnostic.

2. Observations and Reduction

The observations analysed in this paper were obtained with the universal spectrograph (USG) and 40 cm coronograph at Sacramento Peak Observatory on April 30, 1974 (event A) and April 24, 1971 (event B). The USG spectra have a dispersion of approximately 1.6 Å mm^{-1} in the third order used for the high Balmer lines between 3900 Å, and about 5 Å mm^{-1} in the first order used to observe the high Paschen lines between 8250 and 9000 Å. The spectra in the violet and infrared were taken on 103 AG and 2424 films, respectively, with typically five-second exposures.

Examination of the Hα slit-jaw pictures (Figure 1) taken with the spectra of event A shows an extremely bright condensation rising from behind the limb to a height of about 1×10^5 km within 10 min, at a mean speed of about 135 km s^{-1} during the time the spectra analysed here were obtained. The spectra show strong emission in the hydrogen and neutral helium lines, and also in the He II line λ4686. However, Fe XIV emission at λ5303 is very weak and no Ca XV emission is detected at all. This relatively low-temperature spectrum for such a bright object is characteristic of an active prominence rather than a limb flare.

Of the SPO spectra obtained of this prominence, only one, obtained in the brightest initial condensation, shows the high Paschen lines. The corrsponding slit-jaw picture is shown in Figure 1(b). The highest Paschen series lines in this first-order spectrum are shown in Figure 2(a). The highest Balmer lines observed in the nearly simultaneous and co-spatial third-order spectrum, obtained 40 s earlier, are shown in Figure 2(b). The corresponding slit-jaw picture appears in Figure 1(a). The USG spectra also include the Mg I triplet near 3830 Å, and the Sr II λ4078 line, whose ratio is density sensitive (Landman, 1984). Event B exhibits a similar spectrum with even brighter, and much narrower hydrogen lines.

The spectra were digitized with a PDS microdensitometer and smoothed with a Gaussian filter. The total halfwidth of the smoothing profile produced by the USG slit and this Gaussian filter was 0.17 Å at the Balmer wavelengths. This filter greatly reduced emulsion noise and thus simplified measurement of halfwidths. Several scans were taken along slightly displaced paths of reduce noise due to alignment uncertainties and small-scalef plasma inhomogenieties. Separate, co-aligned scans were obtained through the Mg I triplet lines and the Sr II λ4078 line on the same film to evaluate the density-sensitive line intensity ratio.

3. Analysis and Results

3.1. Electric Field from the Paschen-Line Stark Broadening

The fullwidths at half intensity $\Delta\lambda_{1/2}$ of the Paschen lines emitted in event A are shown in Figure 3(a), plotted against the upper quantum number up to P_{21}. The lines P_{15} and

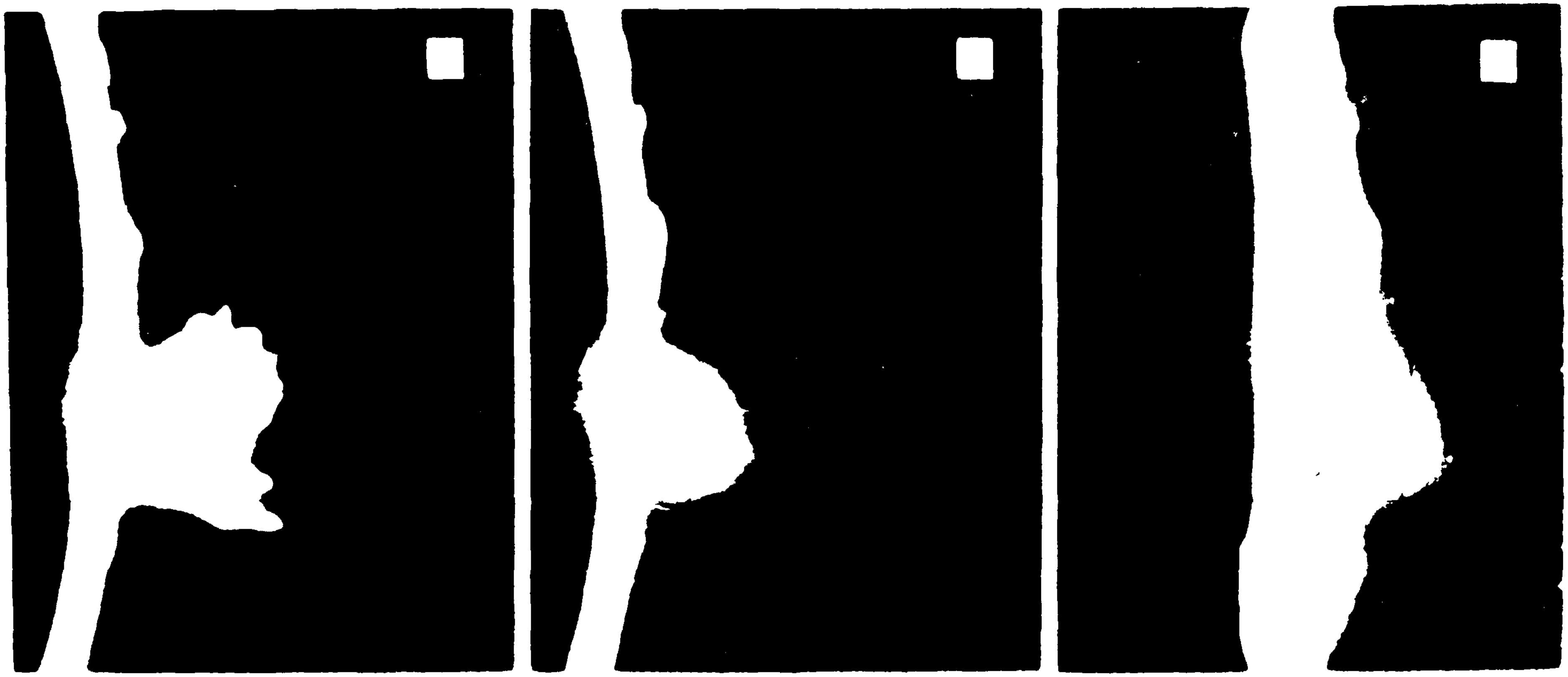

Figure 1. $H\alpha$ slit-jaw images of the 30 April 1974 prominence (event A). The curved spectrograph slit is oriented parallel to the limb. The Balmer spectrum analyzed here was taken with the first image (a) at 17:59:20 UT. The Paschen spectrum was taken with the second image (b) at 18:00:00 UT. Note that the slit has moved slightly in the second image. The third image (c) was taken at 18:06:40 UT.

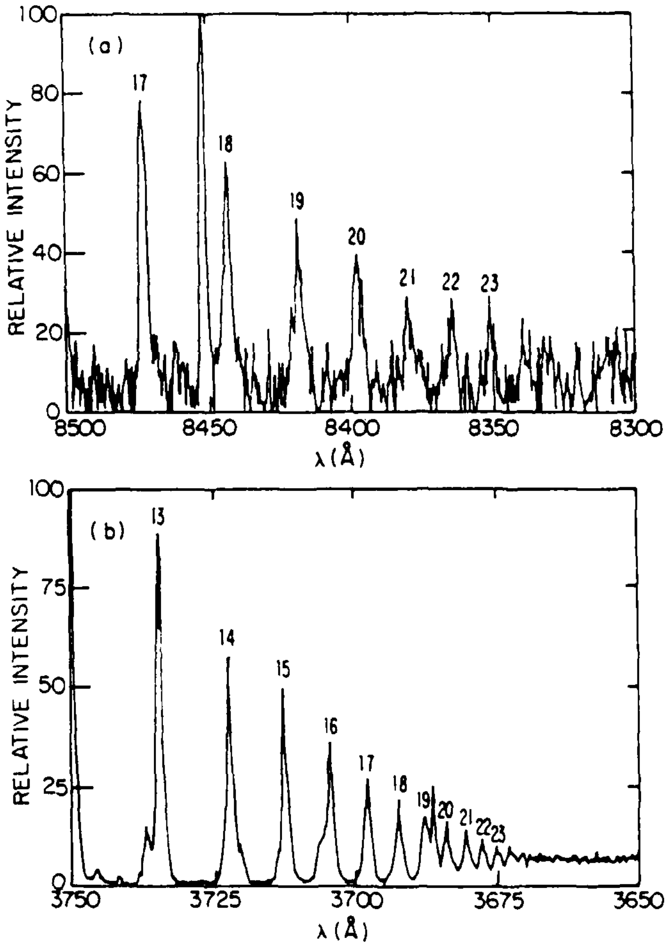

Fig. 2. Microdensitometer scans with the background subtracted of (a) the high Paschen lines and (b) the high Balmer lines. Instrumental broadening has not yet been removed in the scans shown here.

P_{16} are not measured because of evident blends. The symbols give the four individual measurements of each line, and the solid curve is a least squares quadratic fit to these data. The instrumental smoothing has been removed from the halfwidths.

The lines are quite broad, even at P_{10}, where Stark effect is negligible even at field intensities of order 10^2 V cm^{-1}. This indicates a large turbulent Doppler broadening of about 60 km sec^{-1} after thermal broadening corresponding to $T = 8 \times 10^3$ K is removed. The increasing width of the lines with decreasing Paschen number below P_{15} is caused by self-absorption. The increasing width with Paschen number above P_{15} is caused by Stark effect in the optically thin high members of the series.

The dashed curves in Figure 3(a) represent the line widths expected (bottom to top) due to total electric fields of 35, 55, and 100 V cm^{-1} in the hydrogen-line emitting plasma. These Stark-broadening curves are calculated from data on the displacements and intensities of Stark components of the hydrogen lines to $n = 18$, given by Underhill and Waddell (1959). The Stark effect broadening gives rises to a line profile function $S(x)$ where $x = \Delta\lambda/F_0$ is the displacement from line center, and F_0 is the Holtzmark field intensity quoted above. The Holtzmark field used here provides a better basis for comparison with motional or wave-related electric fields than does the mean particle field (Griem, 1974) which exceeds it in magnitude by roughly a factor 3. The functions $S(x)$ for each line were convolved with Gaussian profiles representing the additional instrumental and Doppler broadening to produce the calculated curves ploted (dashed) in Figure 3(a).

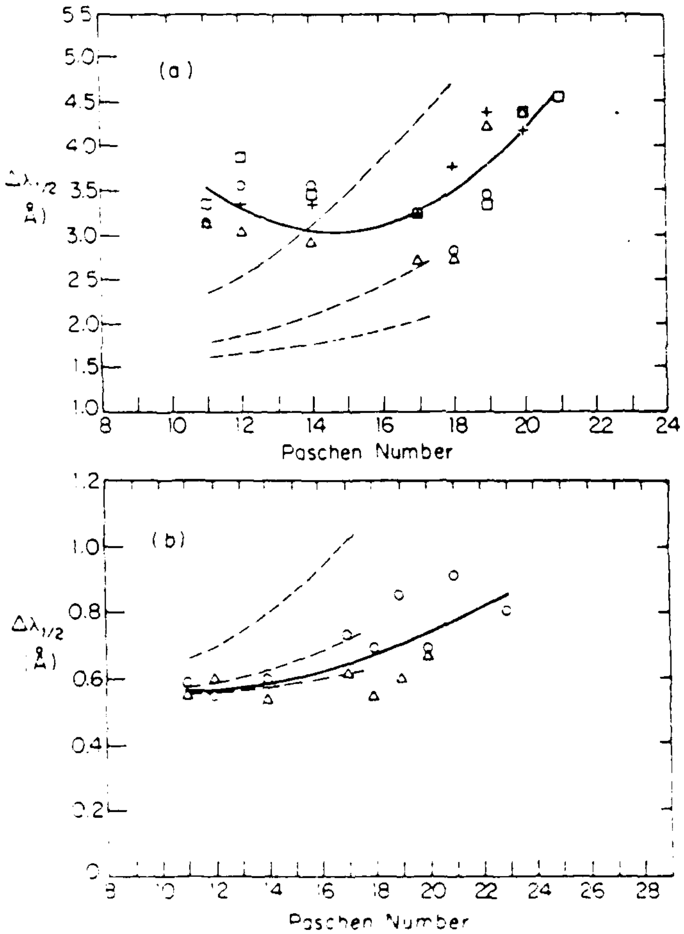

Fig. 3. Plots of $\Delta\lambda_{1/2}$ against quantum number for the Paschen series in event A (a) and in event B (b). The solid lines represent a least squares quadratic curve fit to the data. Common symbols represent separate microdensitometer scans of the same spectrum. The dashed curves calculated for the Holtzmark field strengths of (bottom to top) 35, 55, and 100 V cm^{-1} in (a), and 7.5, 12, and 22 V cm^{-1} in (b).

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The slope of the plot of the observed halfwidths for $P > 16$ in Figure 3(a) indicates a total field of roughly 50 V cm^{-1} for event A. A similar analysis for the much narrower Paschen lines measured out to P_{23} in event B is shown in Figure 3(b). The total electric field derived for that event is much lower, approximately 10 V cm^{-1}.

3.2. Electric field from the Balmer-line Stark effect

A similar analysis has also been carried out on the high Balmer lines, whose profiles in event A are shown in Figure 2(b). The halfwidths corrected for instrumental smoothing for event A are plotted to B_{23} as the solid line in Figure 4(a). The theoretical halfwidths plotted as dashed lines in Figure 4(a) were calculated from the Underhill and Waddell (1959) tables and convolved with suitable Gaussian profiles to represent the

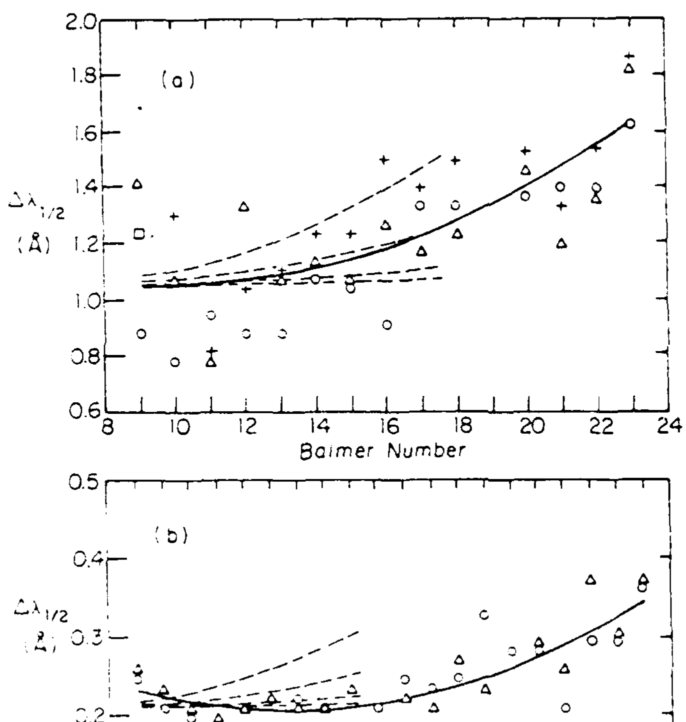

Fig. 4 Same as Figure 3, but for the high Balmer lines of (a) event A and (b) event B. The dashed curves refer here (*bottom* to *top*) to Holtzmark fields of 35, 55, 100, and 170 V cm^{-1} in (a), and to fields of 7.5, 12, 22, and 35 V cm^{-1} in (b).

thermal and turbulent broadening. Comparison with the halfwidth calculations of Kurochka (1969), which take into account electron impact corrections, shows good agreement over the density range of interest here. Comparing the absolute slopes of the calculated curves with those given in Figure 3, we see that the Paschen-line Stark broadening is much more sensitive to small electric fields than is the Balmer-line broadening.

The slope seen in the observed Balmer line halfwidths is event A is best fitted by the theoretical curve for an electric field of $E \sim 150\ \mathrm{V\ cm^{-1}}$. But the increasing wing blending of the broad Balmer lines observed in event A makes it progressively more difficult to identify the true zero level, and thus acts to gradually increase the measured halfwidth with Balmer number. This effect tends to increase the apparent total field measured, and an accurate correction is difficult. As seen in Figure 2, the effect is less serious in the Paschen lines, whose spacing is greater relative to their width.

The turbulent broadening of the Balmer lines for event A is approximately 48 km s^{-1}, thus somewhat less than might be expected simply from wavelength scaling of the Gaussian component of the Paschen lines. Some difference in electric field and turbulent broadening from the Balmer and Paschen lines is expected, given the rapid evolution of the structure and the slightly different split pointing between the Balmer and Paschen spectra (Figures 1(a, b)).

Figure 4(b) shows the results of the Balmer line reduction for event B. Balmer lines up to B_{28} were measured. Their much narrower width compared to event A makes the blending effect mentioned above less important. A total field of about 18 V $\mathrm{cm^{-1}}$ is derived.

3.3. Plasma density from a line ratio diagnostic

The measured values of the line intensity ratios $R = I(\mathrm{Mg\,I}\ \lambda\lambda 3833 + 3838)/2I(\mathrm{Sr\,II}\ \lambda 4078)$ are presented in Table 1 for events A and B. In event A the average value of the ratio $R = 3.0 \pm 0.25$ yields an electron density in the range $10^{11.9} > n_e > 10^{12.2}$, assuming $T = 8 \times 10^3$ K, and using the plot of R against n_e given in Figure 4 of Foukal *et al.* (1986). These density values would be lowered by about a factor two if $T = 5 \times 10^3$ K is assumed for the temperature in the region forming the Mg I and Sr II lines. The corresponding density range at $T = 8 \times 10^3$ K indicated by the ratio values measured for event B is $10^{11.2} < n_e < 10^{11.5}\ \mathrm{cm^{-3}}$.

Other sources of uncertainty in relating this line ratio to density are discussed by Landman (1983, 1984). The ratio in event A does not seem to be affected significantly by self-absorption since the line intensities of the three Mg I triplet lines is within 10% of the 5 : 3 : 1 ratio expected for an optically thin plasma (see Table I). In event B some evidence for appreciable optical depth is seen in the strongest (λ3838) line of the Mg I triplet.

The high turbulent velocities in event A would tend to decrease the ratio, so the true densities might be somewhat higher than those quoted. However, this effect can be neglected in event B, where turbulent broadening is below 5 km s^{-1}. The position of the Mg $\lambda\lambda$3838 lines on the wings of the bright Balmer line B_9 would also tend to increase

TABLE I

Event A				
	Scan 1	Scan 2	Scan 3	Average
$I(\lambda 3838)$	10.8	11.4	9.7	10.6
$I(\lambda 3833)$	8.3	7.2	6.5	7.3
$I(\lambda 3830)$	2.2	2.6	2.6	2.5
$I(\lambda 4078)$	2.9	3.1	2.9	3.0

Event B			
	Scan 1	Scan 2	Average
$I(\lambda 3838)$	3.9	3.4	3.6
$I(\lambda 3833)$	2.8	2.6	2.7
$I(\lambda 3830)$	1.2	1.0	1.1
$I(\lambda 4078)$	5.9	2.4	4.1

the ratio. But we believe that uncertainties due to the above effects seem unlikely to influence the density by more than the factor two already implied by the temperature uncertainty noted above, particularly in event B.

4. Discussion and Conclusions

A fully-ionized hydrogen plasma of density N is expected to give rise to a Holtzmark electric field $F = 4.1 \times 10^{-7} N^{2/3}$ V cm^{-1}. The field values thus implied by the density range quoted above for event A are between 30 and 45 V cm^{-1}. For event B they lie between 10 and 15 V cm^{-1}.

The total electric field of between 10–18 V cm^{-1} measured by both the Paschen and Balmer lines in event B thus corresponds well with the Holtzmark field derived for that eruptive prominence. In event A, the more accurate measurements obtained from the Paschen lines, which indicate a total field of 50 V cm^{-1}, also agree very well with the Holtzmark field for that structure. The higher field obtained from the Balmer lines in that case seems to be explainable as the result of wing blending given the extremely broad hydrogen lines in that structure.

These results indicate that the total electric field measured in these eruptive prominences can be explained as a pressure broadening field. Macroscopic fields due to reconnection or plasma waves might exist in these prominence plasmas, but their magnitude over volumes whose hydrogen line emission measure is appreciable must be of order 10 V cm^{-1} or less.

The horizontal and radial expansion rates of event A ove the ten-min time period after these spectra were obtained yield a mean rate of motion of 135 km s^{-1}. If we associate this expansion rate observed in Hα with a reconnection speed (Kopp and Pneuman, 1976), we find that the motional electric field $E = V \times B$ associated with reconnection at this rate might be of order 10 V cm^{-1} if the magnetic field at coronal heights in this structure were of order 100 G. Measurement of the actual electric fields that might be present near the neutral point in reconnecting structures will provide an important test of reconnection models (e.g., Kopp and Poletto, 1984).

Better discrimination of the roles played by pressure broadening and macroscopic electric fields in Stark broadening observed in coronal structures will require application of the polarization diagnostic described by Foukal *et al.* (1986). The errors inherent in comparing absolute electric fields measured by the two different techniques of Stark broadening and line ratio densities used here is eliminated in that approach. The polarization signature, if clearly detected, can then only be interpreted in terms of macroscopic electric fields. We have shown here that the much higher Stark sensitivity of the Paschen lines makes these lines suitable for investigation of macroscopic fields of order 10 V cm^{-1} and below.

Acknowledgement

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