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Comparison of High-Resolution Solar Irradiance Spectra and the Solar Luminosity in the Period 1980-1989

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1. Introduction

In this research we aim to determine to what extent the solar irradiance changes measured through the 1980's from orbiting vehicles are accompanied by spectroscopic irradiance changes observable from the ground. We describe fractional changes in line absorption as 'blanketing'.

In Section 2 we briefly review results obtained in an earlier project and which have been published. Section 3 describes the data of this investigation; Section 4, the data reduction; Section 5, the observational results in terms of blanketing; and Section 6, interpretation of the measured changes. Section 7 contains an outline of possible uses for doppler-shift data that emerges with the measurements of the blanketing variations. Section 8 is an outline for future research suggested by our results in this project.

2. Earlier Blanketing Work

We concluded that solar line blanketing appears to change with time. Data were taken from irradiance spectra got with the Fourier Transform Spectrometer (FTS) of the National Solar Observatory on 1987 October 14. A comparison of the 1987 October spectrum with the National Solar Observatory Atlas (NSO1) (Kurucz et al. 1984) of 1981 March was carried out in selected regions between 321.9 and 852.3 nm. Blanketing changes of about one per cent were evident in all the spectral regions examined. The changes from approximate solar maximum in 1981 to approximate solar minimum in 1987 corresponded to line strengthening.

A simple model was offered to sort out our observed blanketing change from the measured irradiance change using the blanketing in NSO1. Our results were reported in "Comparison of High Spectral Resolution Atlases of Integrated Sunlight and the Solar Luminsoity from Two Epochs", the final report to the National Aeronautics and Space Administration for Grant No. NAG 5-768, June 1988. The changes from approximate solar maximum in 1981 to approximate solar minimum in 1987 corresponded to line strengthening.

For our published paper (Mitchell and Livingston 1991) we used the FTS data obtained by W. C. Livingston (WCL) in 1987 January 6, somewhat closer in time to the solar minimum of late 1986.

An analysis of all the unblended lines between 500.5 and 560 nm revealed a blanketing increase, solar maximum to minimum, of about one per cent.

Our model of the blanketing changes was expanded to take into account spots, plages, and the facular network. An important conclusion emerged in the realization that the more blanketing there is in a given spectral region, then the greater will be the effect in that region of the blanketing changes producing irradiance changes. The main uncertainties lie in our poor knowledge of the facular continuum contrast and of the existence of any unresolved facular network.

3. Observations

The FTS database has been supplied mostly by WCL. He has been making irradiance spectra with the FTS that cover the interval from the solar maximum of 1980/81 to that of 1989 in the wavelength range 500 to 560 nm. He kindly provided me with spectra representative of each of the years 1981 though 1985 and 1987 through 1989. In general these data (see Table 1) refer to the last third or quarter of each year. Since the already published data (Mitchell and Livingston 1991) refer to 1987 January 6, those results will, for the purpose of this report, be considered representative of 1986.

Spectra were also obtained by Claude Plymate and myself at two-week intervals in 1987 October and 1989 October for the purpose of sampling the sun at consecutive half rotations. The study of blanketing variations through the solar rotation was great aided by the existence of WCL's dataset of 1982 November, which spans 26 days of that month.

4. Data Reduction

The reduction of this type of data is described rather completely in Mitchell and Livingston (1991). In that work the behavior of blended lines was found to be so much like that of unblended lines that the distinction was dropped in the present study. The study of line dips was also dropped when it was realized that the FTS parameters adopted for the 1987 October and 1989 October atlases appeared to yield systematically deeper lines than for NSO1. While an effectively higher spectroscopic resolution produces deeper lines, the equivalent widths should be unaffected. The main interest in the dips has been to get a measure of a given line width from the ratio of the equivalent width to the dip of that line. The line width, of course, contains information on the photospheric turbulent spectrum as well as the solar rotation. We will discuss this further in Section 7 below, but in this report we will concentrate primarily on the blanketing variations.

5. Blanketing Variations

5.1 Solar Cycle

The line changes are summed up on an annual basis in the Figures 1 through 8, in which the relative equivalent widths, less unity, are plotted against the logarithm of the equivalent widths in NSO1. The relative equivalent widths are everywhere taken with the NSO1 value in the numerator and the non-NSO1 value in the denominator. In other words, we are ratioing the solar maximum equivalent widths to the off-maximum equivalent widths.

All of these plots show 1 to 2 per cent mean errors for the observation of a single line. The overall blanketing variation, i.e. the difference from the NSO1 standard, is least in 1981 and 1989, dates at or near solar maximum. In the intervening years that variation covers a considerable range: 1/2 to 2 per cent. The tendency is for the lines to strengthen away from maximum.

A correlation can be found between the blanketing variation and other measures of the solar activity like the irradiance or sunspot number. Table 2 contains these correlations: blanketing variation vs. 1) irradiance, and 2) monthly relative sunspot number (MRSN).

Correlation coefficients are never to be construed as proof or evidence of cause and effect. At best they indicate a physical situation where two or more effects derive directly or indirectly from a common cause.

5.2 Solar Rotation

The 1982 data cover 26 days or a full solar rotation. The blanketing variation shows a considerable range, as it does between 1982 and 1988, in this case, 1/4 to 2 3/4 per cent. We have calculated the correlation coefficient of this blanketing variation against the irradiance and against the sunspot numbers. The results are in Table 2.

5.3 Line-to-line Correlations of Blanketing Variations

A small sample from our database of spectrum line blanketing changes was examined to test the consistency of the line behaviors, day-to-day and year-to-year. The day-to-day results from the eleven observation files covering four days in the last third of late October 1983 show correlation coefficients for the equivalent widths of 21 line pairs that range from +0.74 to -0.39. There are no obvious trends with line strength or atomic species. Sixty-two percent of the coefficients were positive. This result suggests that there is some degree of consistency in the day-to-day behavior of the line blanketing variations in different lines relative to each other. In other words, the 'relative-equivalent-widths vs. equivalent-width' plots are not mere scatter diagrams unrelated from one day to the next.

On the scale of the solar cycle, four selected line pairs from the blanketing atlases were correlated on a year-to-year basis, giving coefficients of +0.61 to +0.94. The equivalent-width ratios were compared in this case. The high correlations suggest that a solar cycle dependence of the blanketing variation is demonstrated more clearly than changes of a day-to-day nature.

6. Interpretation of Blanketing Variations

The correlation coefficients in Table 2 show, for the 1982 data, the blanketing variation to have a high (negative) correlation with the irradiance data from the Active Cavity Radiometer Irradiance Monitor (ACRIM). Qualitatively we suggest that away from high activity the spectrum associated with the active sun weakens, giving way to the slightly more heavily blanketed spectrum of the quiet sun. Reduced absorption in the plage and facular spectra more than compensates the enhanced absorption in the spot spectrum, giving a net line weakening at high solar activity, or line strengthening away from low solar activity.

The 26-day time scale of the 1982 FTS data points to the possible influence of the solar rotation in presenting unlike solar hemipsheres sequentially to the observer. The 1989 October data obtained to test this possibility show the changes in blanketing and irradiance to be of opposite sign through one half of a rotation.

But in Table 2 we find that the blanketing and the irradiance have a correlation coefficient of approximately +0.25 for the cycle-long interval. This paradox--runs of data for the same phenomena giving contrary correlations--may be resolved when we realize that oscillatory functions of different period can yield quite different correlation coefficients depending on the window of time over which the data are being compared. The low positive correlation of irradiance with blanketing over the solar cycle is swamped by a high negative correlation operating over the solar rotation. On the other hand, the negative correlation is smeared out over the solar cycle because the data are averaged within each year.

7. Velocities

The measurement of doppler shifts is accomplished for hundreds of lines in the FTS irradiance spectra. Our data reduction finds the shift common to all of the lines in a given observation and, subsequently, the shift of each line. The former reflects the earth's rotation and heliocentric and barycentric motions to the extent those motions differ from those for NSO1. The latter show how the photospheric layers are moving radially in relation to the NSO1 epoch. For the former, Table 3 lists the velocities for about half of the observational files in this study. An example of the latter are the shifts for 643 photospheric lines shown in Fig. 9.

8. Future Research

The database of already-measured line blanketing variations covers the range 500-560 nm. FTS atlases containing the raw material for blanketing measurements at different levels of solar activity cover the range 300-1000 nm. The wealth and variety of absorption lines in these optical spectra point to an important next step in the interpretation of the blanketing-change data, namely their examination by magneticity and depth-of-line formation. The line chnages can serve as probes of changes in the magnetic and velocity fields in the course of the solar cycle.

Perhaps of greatest importance, however, is finding the spectral distribution of the irradiance changes by measuring the blanketing changes along the spectrum. The far greater blanketing in the ultraviolet suggests that a disproportionly large fraction of the irradiance change is to be found in the ultraviolet.

Acknowledgments

We are indebted to W. C. Livingston and Kitt Peak staff, particularly G. Ladd, for supplying the FTS data for this investigation. P. Hantzios and J. Yencho assisted in the early stages of the project. Members of the Academic Computing Services staff of the Ohio State University have frequently provided invaluable help.

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TABLE 1A

BLANKETING OBSERVATIONS AND RESULTS
Day by day

Year		File No.	Date	Julian Day - 2440000	Fractional Blanketing Change	Irradiance (W/M^2) ACRIM	Irradiance (W/M^2) NIMBUS	Monthly Relative Sunspot Number
1981	A	FL01	09/13/81	4861	0.0023		1370.82	132
		FL02	09/13/81	4861				
	B	FL03	09/14/81	4862	0.0035		1370.57	148
		FL04	09/14/81	4862				
		FL05	09/14/81	4862				
		FL06	09/14/81	4862				
1982	A	FL07	11/02/02	5276	-0.0272	1368.96	---	88
		FL08	11/02/82	5276				
	B	FL09	11/03/82	5277	-0.0283	1368.05	1371.73	75
		FL10	11/03/82	5277				
		FL11	11/03/82	5277				
		FL12	11/03/82	5277				
		FL13	11/03/82	5277				
	C	FL14	11/04/82	5278	-0.0267	1368.46	1371.12	100
		FL15	11/04/82	5278				
		FL16	11/04/82	5278				
		FL17	11/04/82	5278				
	D	FL18	11/05/82	5279	-0.0122	1368.08	1371.29	100
	E	FL19	11/06/82	5280	0.0001	(1367.38)	---	76
		FL20	11/06/82	5280				
	F	FL21	11/07/82	5281	-0.0026	1368.01	1371.21	106
		FL22	11/07/82	5281				
	G	FL23	11/11/82	5285	0.0010	1367.36	1370.87	112
		FL24	11/11/82	5285				
	H	FL25	11/12/82	5286	-0.0058	1366.96	1370.22	83
		FL26	11/12/82	5286				
		FL27	11/13/82	5286				
		FL28	11/13/82	5286				
	I	FL29	11/21/82	5295	-0.0164	1368.10	1369.49	131
		FL30	11/21/82	5295				
	J	FL31	11/24/82	5298	-0.0058	1366.96	1370.35	96
		FL32	11/24/82	5298				
	K	FL33	11/27/82	5301	-0.0183	1367.95	1371.44	71
		FL34	11/27/82	5301				

TABLE 1A
(cont'd)

Year		File No.	Date	Julian Day - 2440000	Fractional Blanketing Change	Irradiance (W/M^2) ACRIM	Irradiance (W/M^2) NIMBUS	Monthly Relative Sunspot Number
1983	A	FL36	10/21/83	5629	-0.0009		1371.09	18
	B	FL37	10/29/83	5637	-0.0065		1370.47	16
		FL38	10/29/83	5637				
		FL39	10/29/83	5637				
	C	FL40	10/30/83	5638	-0.0049		1370.36	15
		FL41	10/30/83	5638				
		FL42	10/30/83	5638				
		FL43	10/30/83	5638				
		FL44	10/30/83	5638				
	D	FL45	10/31/83	5639	-0.0040		1370.49	19
		FL46	10/31/83	5639				
1984		FL47	11/05/84	6010	-0.0073		1369.97	12
		FL48	11/05/84	6010				
		FL49	11/05/84	6010				
		FL50	11/05/84	6010				
		FL51	11/05/84	6010				
		FL52	11/05/84	6010				
		FL53	11/05/84	6010				
		FL54	11/05/84	6010				
1985		FL55	12/20/85	6419	-0.0107		1371.01	24
		FL57	12/20/85	6419				
		FL58	12/20/85	6419				
		FL59	12/20/85	6419				
1987		FL60	10/05/87	7074	-0.0059		1371.44	48
		FL61	10/05/87	7074				
		FL62	10/05/87	7074				
		FL63	10/05/87	7074				
		FL64	10/05/87	7074				
		FL65	10/05/87	7074				
		FL66	10/05/87	7074				
		FL67	10/05/87	7074				
1988		FL68	10/03/88	7438	-0.0073		1372.03	129
		FL69	10/03/88	7438				
		FL70	10/03/88	7438				
		FL71	10/03/88	7438				
		FL72	10/03/88	7438				
		FL73	10/03/88	7438				

TABLE 1A
(conc.)

Year	File No.	Date	Julian Day - 2440000	Fractional Blanketing Change	Irradiance (W/M^2) ACRIM	Irradiance (W/M^2) NIMBUS	Monthly Relative Sunspot Number
1989	FL75	12/04/89	7865	0.0002		1372.77	182
	FL76	12/04/89	7865				
	FL77	12/04/89	7865				
	FL78	12/04/89	7865				
	FL79	12/04/89	7865				
	FL80	12/05/89	7865				
	FL81	12/05/89	7865				
	FL82	12/05/89	7865				
	FL83	12/05/89	7865				
	FL84	12/05/89	7865				
	FL85	12/05/89	7865				
	FL86	12/05/89	7865				
1989	Solar Rotation (Mitchell/Plymate atlases)						
Files	1 - 4	10/01/89		0.0003		1372.78	
Files	1, 2	10/13/89				1373.91	
				-0.0014		(1373.26)	
Files	9 - 12	10/14/89				1372.61	

TABLE 1B

BLANKETING RESULTS
Year by year

		NIMBUS			NIMBUS
81	0.0034	1370.695	85	-0.0107	1371.01
82	-0.0153	1370.858	87	-0.0059	1371.44
83	-0.0043	1370.603	88	-0.0073	1372.03
84	-0.0073	1369.97	89	0.0002	1372.77

Additional points:

	Fractional Blanketing	NIMBUS
NSO1 Atlas 1981 Mar 24	0.0000[a]	1371.08
Published (Mitchell and Livingston 1991) '1986' = 1987 Jan 6	-0.0080	1370.47
1988 NASA Project Final Report: 1987 Oct 14	-0.0081	1371.20

a) Zero by definition since NSO1 is the adopted standard.

TABLE 2

CORRELATION COEFFICIENTS

Blanketing Variation	vs. Irradiance [a]	vs. Monthly Relative Sunspot Numbers (MRSN) [b]
in 1982 November	-0.742 [c] -0.684 [d] -0.307 [e]	+0.353
in 1981 - 1989	+0.237 [f] +0.260 [g] +0.242 [h] +0.233 [i]	+0.470

a) R. C. Willson (1983)
b) Sky and Telescope daily tabulations by A. Koekelenbergh, Sunspot Index Data Center, Brussels.
c) ACRIM, 11 points; d) ACRIM, 9 points; e) NIMBUS, 9 points
f) 8 points (WCL data); g) 9 points including 1987 Jan 6 (in paper by Mitchell and Livingston (1991);
h) 10 points including NSO1 itself; i) 11 points including 1987 Oct 14 (in 1988 NASA Project Final Report)

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h) 10 points including NSO1 itself; i) 11 points including 1987 Oct 14 (in 1988 NASA Project Final Report)

TABLE 3

RADIAL VELOCITIES
(WCL - NS01)

FILE #	(M/S)	FILE #	(M/S)	FILE #	(M/S)
4	420.7	28	143.5	64	879.6
5	482.2	29	174.9	65	902.4
6	547.6	30	-90.4	66	965.0
10	-123.6	31	-90.1	67	994.8
15	-154.6	32	125.3	71	361.0
16	-82.6	33	143.5	72	425.2
17	-13.8	34	174.9	73	473.9
18	328.6	44	-154.3	78	579.7
19	-181.9	45	-147.3	79	645.0
20	-127.9	46	268.3	80	325.4
21	-90.4	50	232.6	81	369.7
22	82.6	51	319.9	82	412.0
23	-187.3	52	386.9	83	466.2
24	-167.9	53	448.1	84	521.5
25	-143.6	54	508.2	85	573.2
26	-90.1	59	621.4	86	74.4
27	125.3	63	846.8		

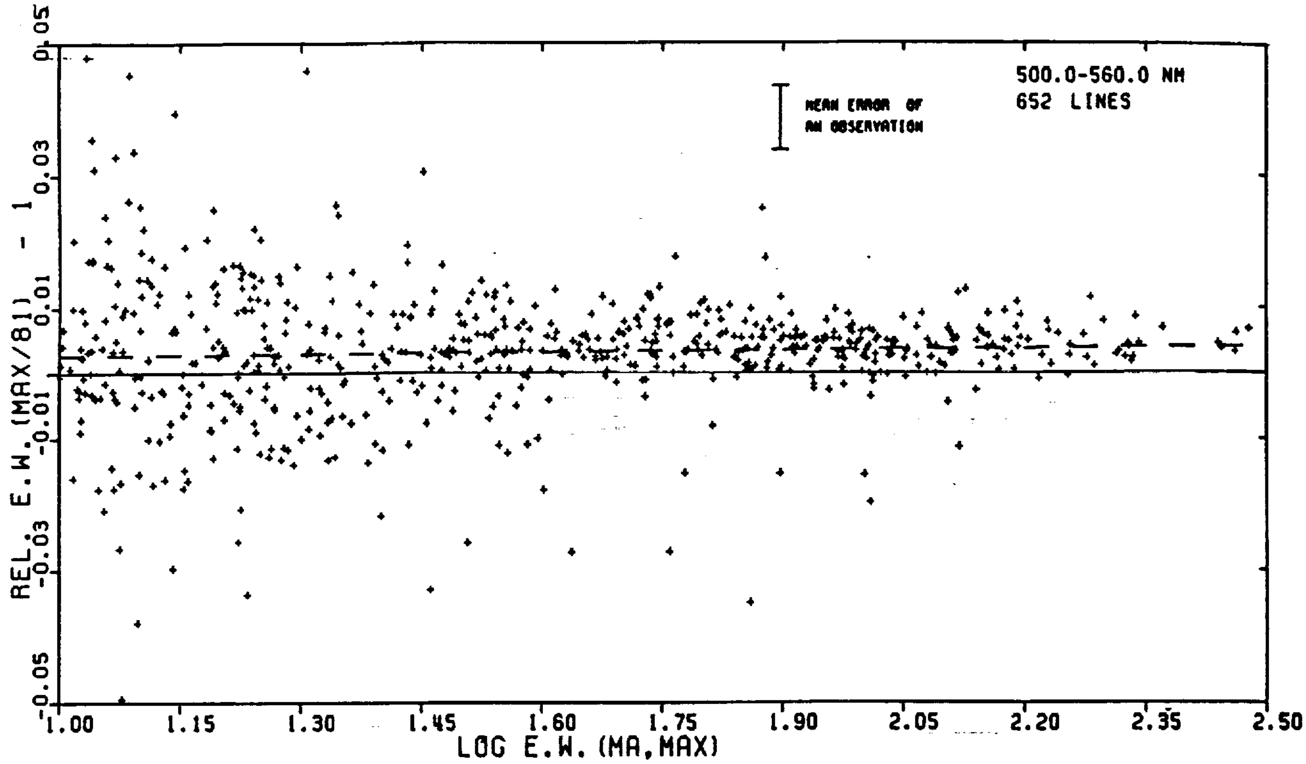

Fig. 1.--Blanketing variation 1981. (Relative equivalent widths (year) - 1) vs log (equivalent width). The dashed line is the least-squares fit to the data. The 'blanketing' for the plot is the ordinate of the least-squares line at the midpoint of the abscissa: 1.75.

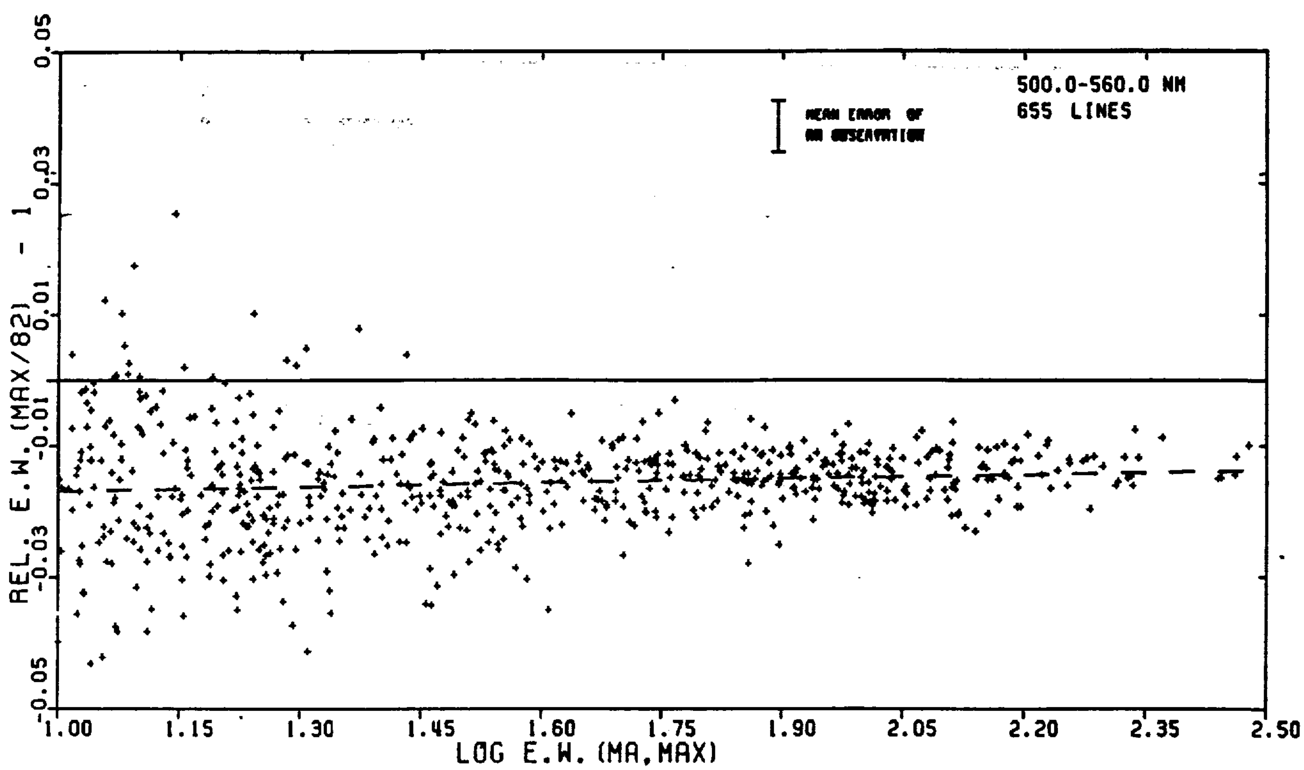

Fig. 2.--Blanketing variation 1982. (Relative equivalent widths (year) - 1) vs log (equivalent width). The dashed line is the least-squares fit to the data. The 'blanketing' for the plot is the ordinate of the least-squares line at the midpoint of the abscissa: 1.75.

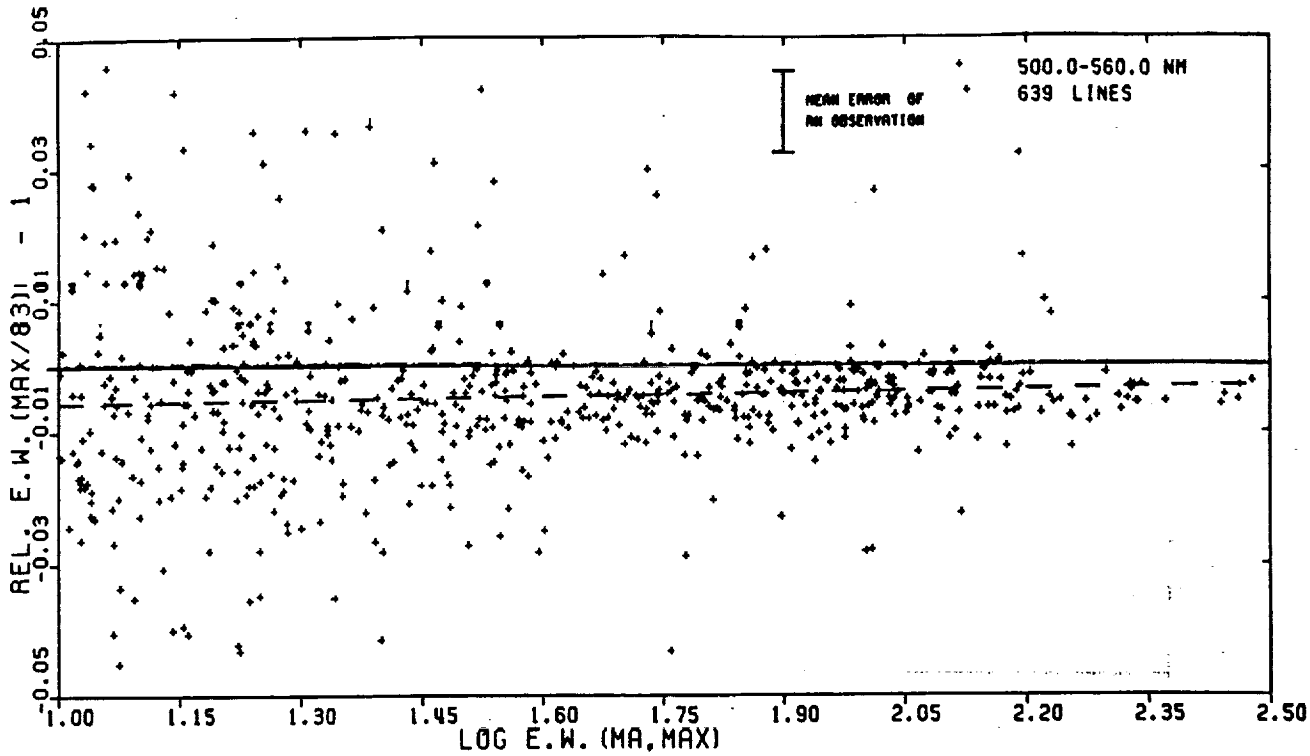

Fig. 3.--Blanketing variation 1983. (Relative equivalent widths (year) - 1) vs log (equivalent width). The dashed line is the least-squares fit to the data. The 'blanketing' for the plot is the ordinate of the least-squares line at the midpoint of the abscissa: 1.75.

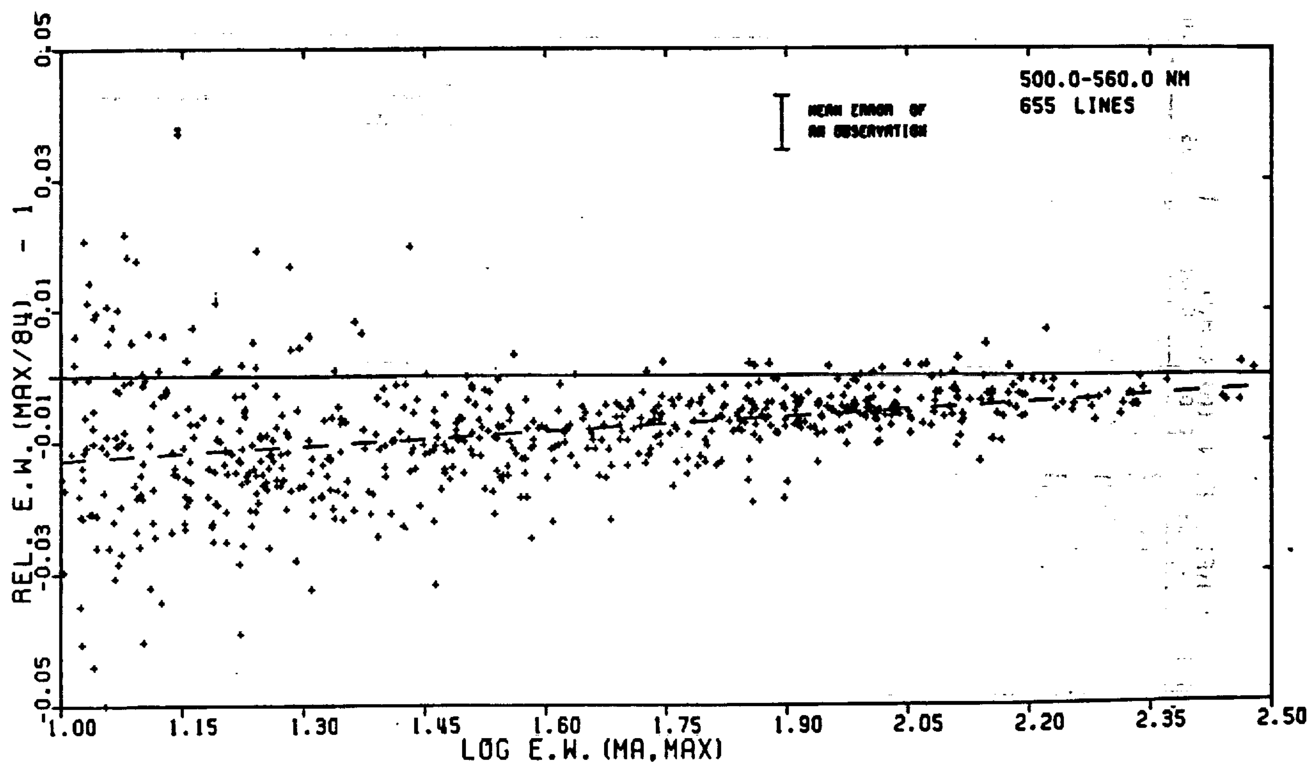

Fig. 4.--Blanketing variation 1984. (Relative equivalent widths (year) - 1) vs log (equivalent width). The dashed line is the least-squares fit to the data. The 'blanketing' for the plot is the ordinate of the least-squares line at the midpoint of the abscissa: 1.75.

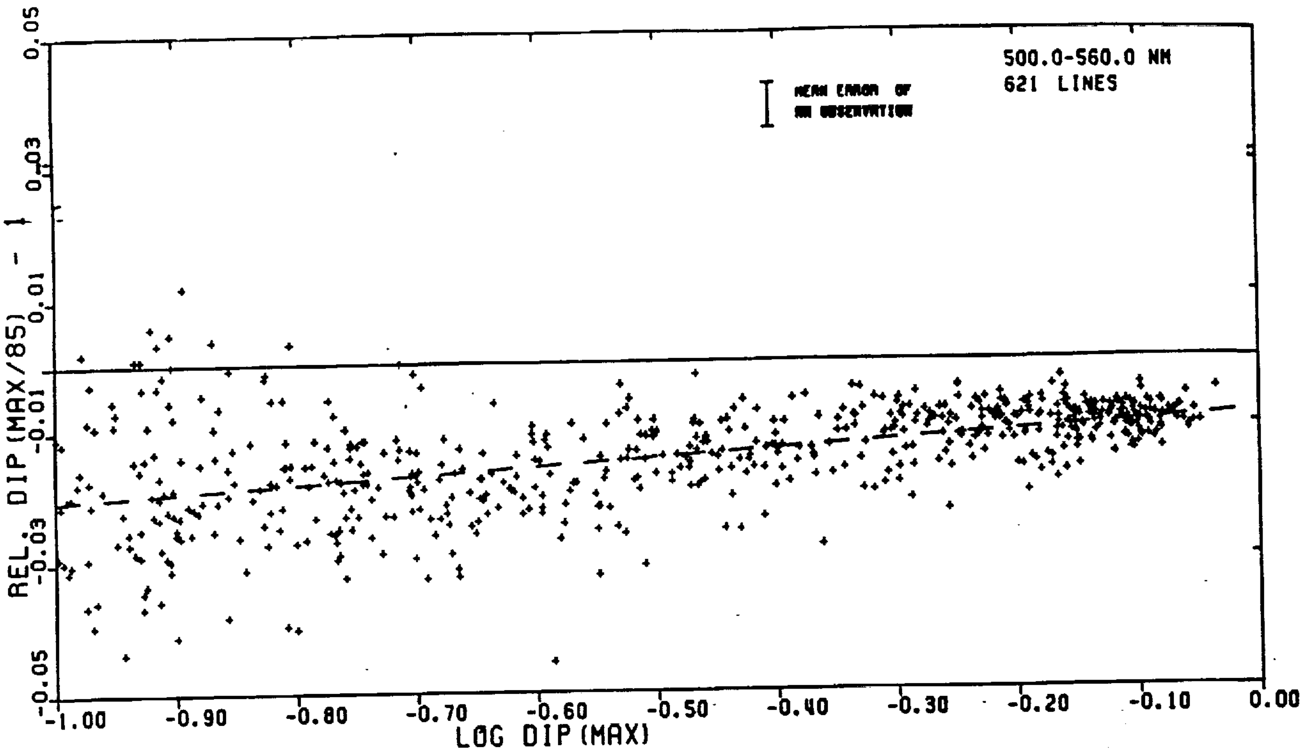

Fig. 5.--Blanketing variation 1985. (Relative equivalent widths (year) - 1) vs log (equivalent width). The dashed line is the least-squares fit to the data. The 'blanketing' for the plot is the ordinate of the least-squares line at the midpoint of the abscissa: 1.75.

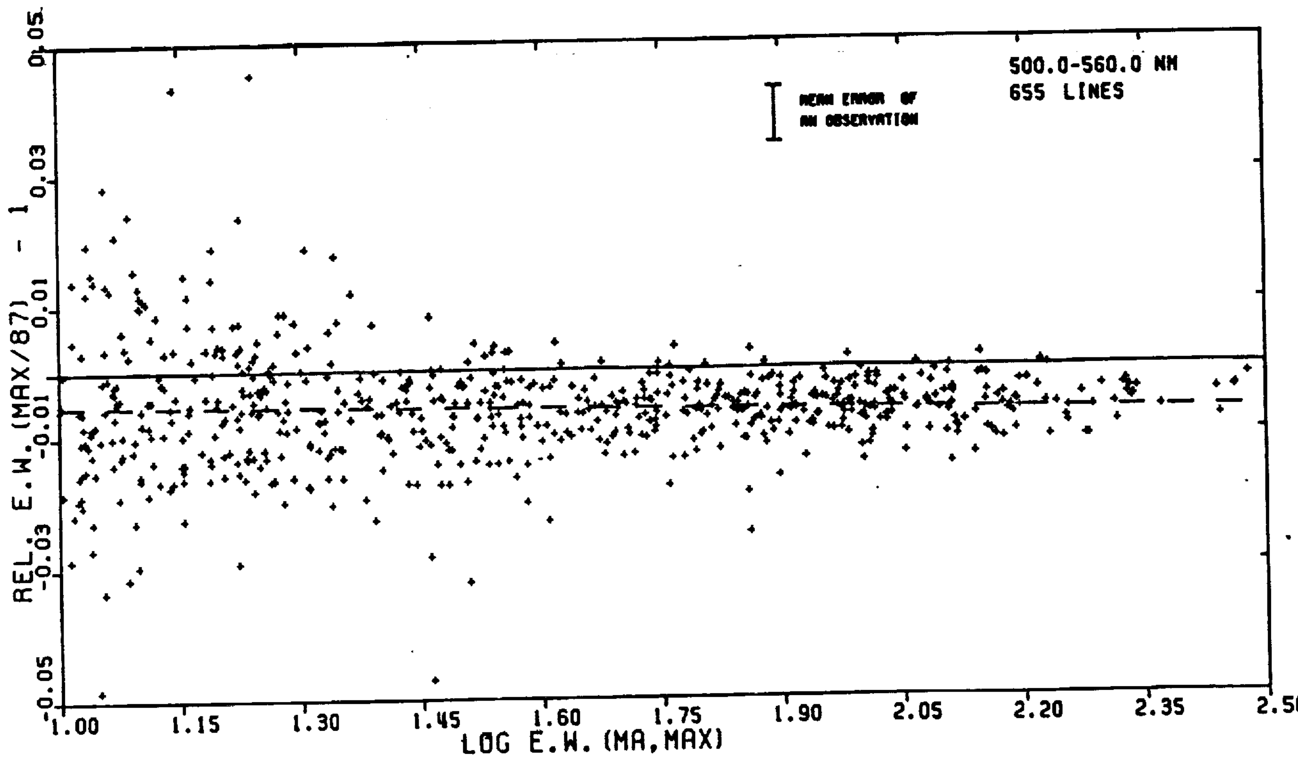

Fig. 6.--Blanketing variation 1987. (Relative equivalent widths (year) - 1) vs log (equivalent width). The dashed line is the least-squares fit to the data. The 'blanketing' for the plot is the ordinate of the least-squares line at the midpoint of the abscissa: 1.75.

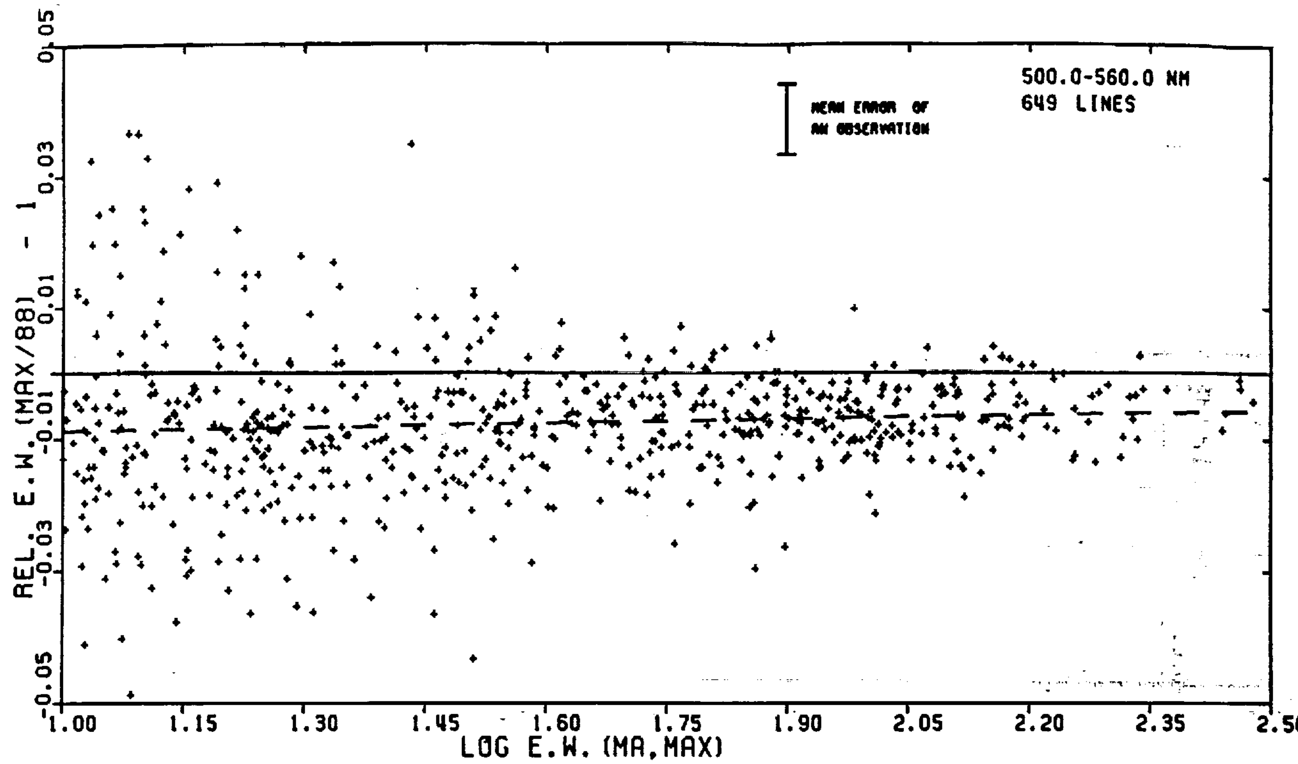

Fig. 7.--Blanketing variation 1988. (Relative equivalent widths (year) - 1) vs log (equivalent width). The dashed line is the least-squares fit to the data. The 'blanketing' for the plot is the ordinate of the least-squares line at the midpoint of the abscissa: 1.75.

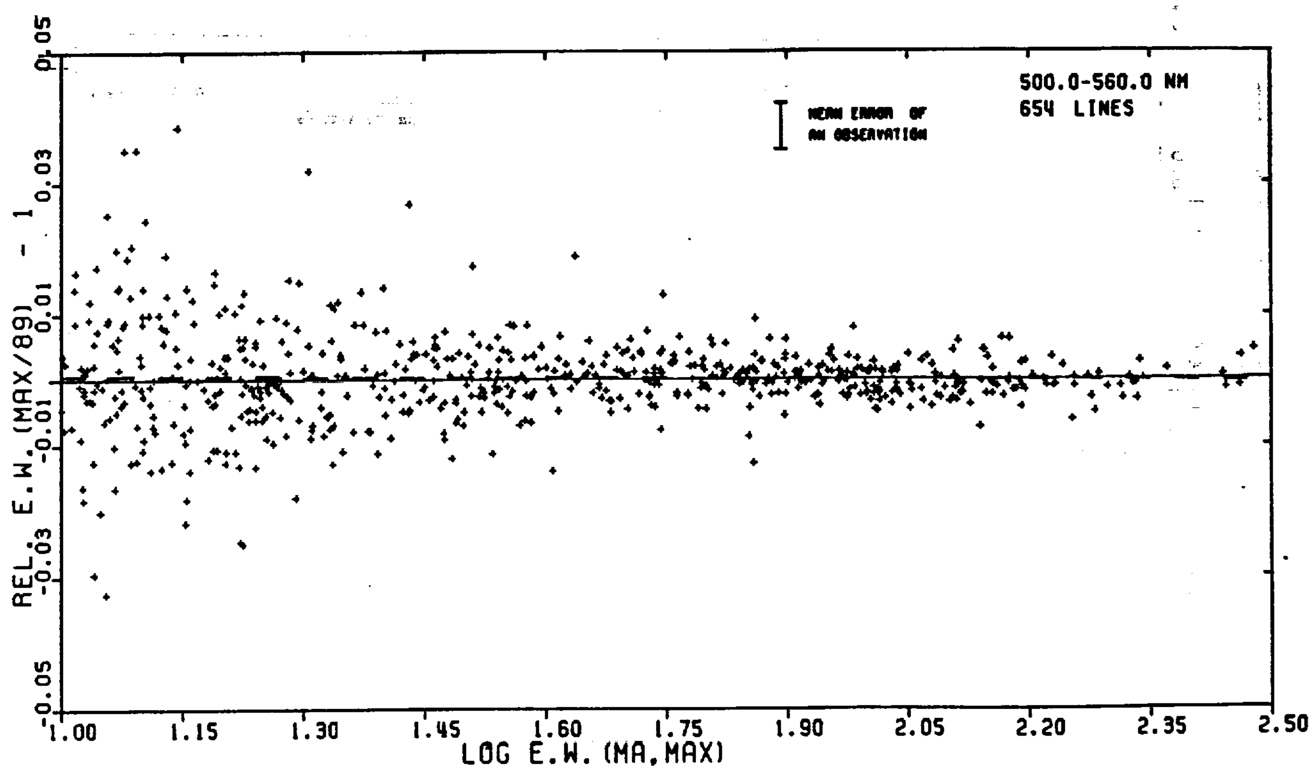

Fig. 8.--Blanketing variation 1989. (Relative equivalent widths (year) - 1) vs log (equivalent width). The dashed line is the least-squares fit to the data. The 'blanketing' for the plot is the ordinate of the least-squares line at the midpoint of the abscissa: 1.75.

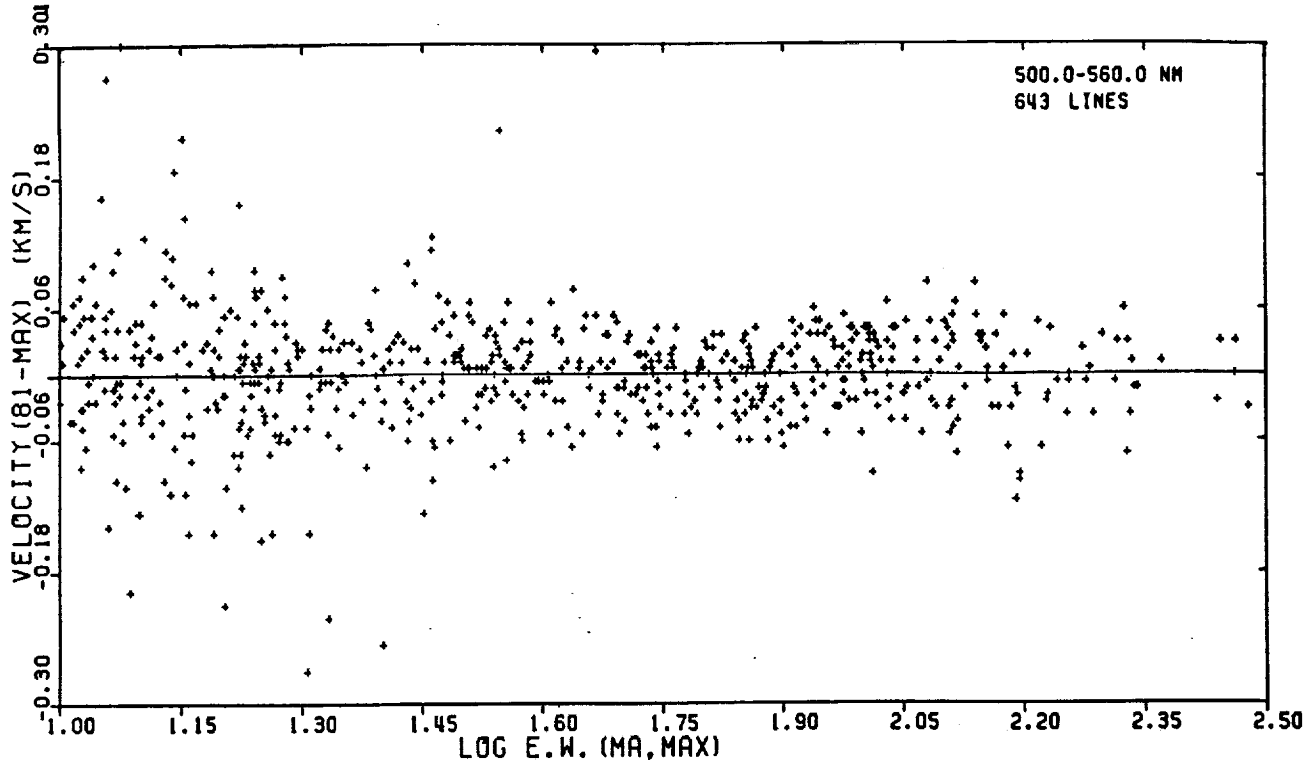

Fig. 9.--Radial velocity shifts measured in the 1981 FTS spectrum plotted against the logarithm of the NSO1 equivalent widths. The shifts are WCL-FTS.