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CONTINUUM EMISSION IN THE 1980 JULY 1 SOLAR FLARE

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ABSTRACT

Comparison of continuum measurements of the 1980 July 1 flare at Big Bear Solar Observatory and Sacramento Peak Observatory show strong blue emission kernels with the ratio of Balmer continuum (Bac):λ3862 continuum:continuum above 4275 Å to be about 10:5:1. The blue continuum at 3862 Å is too strong to be explained by unresolved lines. The Bac intensity was 2.5 times the photosphere and the strongest λ3862 continuum was 2 times the photosphere.

The brightest continuum kernel occurred late in the flare, after the hard X-ray peak and related in time to an isolated peak in the 2.2 MeV line, suggesting that that continuum was excited by protons above 20 MeV.

Subject headings: Sun: flares — Sun: spectra

I. INTRODUCTION

The intense solar flare of 1980 July 1 exhibited strong continuum, radio, and X-ray emission, as well as nuclear γ-ray lines. A magnetic transient was observed, which has been described by Zirin and Tanaka (1981), who have also described the optical flare. In this *Letter* we compare the continuum observations obtained at Sacramento Peak Observatory (SPO) and Big Bear Solar Observatory (BBSO) to determine the spectral distribution in the continuum. We also discuss the relation of the continuum to other data.

We find a definite blue continuum in the 3860 Å region, which is about 5 times brighter than that at longer wavelengths and about half the Balmer continuum (Bac) intensity. We find no linear polarization in the Bac or the optical continuum. Although there are a series of rapid flashes in this event coinciding with the impulsive burst, the strongest continuum occurs in a longer lived patch about 8000 km away, the brightening coinciding in time with a late peak of the 2.2 MeV line reported by Matz *et al.* (1981).

II. OBSERVATIONAL RESULTS

Figures 1 and 2 (Plates L5 and L6) present the SPO and BBSO data at 16:27 and 16:28:30 UT, respectively. The SPO observations were made with a multiband polarimeter (designed by J. M. Beckers), which, by means of a Wollaston prism, simultaneously records a pair of photographs in orthogonal planes of linear polarization. A set of filters provides a sequence of transmissions/bandwidths at 3610/22 Å, 4275/40 Å, 4957/48 Å, 5645/50 Å, and 6203/48 Å. Unfortunately, the SPO instrument was operating at a slow rate, so a full cycle of data was obtained only every 90 s, but at least one wavelength was recorded every 15 s. The seeing was good before the flare but deteriorated during it.

BBSO observations were made every 10 s, using the 65 cm reflector with a 3862/20 Å filter chosen to exclude Balmer line emission. Observations were prevented by clouds before 16:26 UT and after 16:31 UT; luckily, the period of the flare was clear. Data were also obtained in He I D3, Hα, and with the magnetograph.

The BBSO data are discussed in detail by Zirin and Tanaka (1981). Briefly, a brilliant explosive flare was in progress when clouds cleared at 16:26:08 UT. A rapid rise in Hα started at 16:26:47 UT and peaked at 16:27:14 UT. The Hα brightness spread, and a new peak occurred at 16:28:20 UT, followed by an outward explosion. Helium D3 showed four brilliant emission kernels and widespread dark ejecta. The λ3862 frames showed several rapidly varying bright points near the neutral line. These occurred in the area marked A and B in Figures 1 and 2, which show the flare at 16:27:00 UT near the hard X-ray flash and at 16:28:30 UT at the rise of the brightest kernel (point C). The latter kernel exhibited the brightest blue continuum we have ever measured, reaching twice the photospheric intensity at that wavelength. By comparison, Machado and Rust (1974) quote a peak intensity in the Balmer continuum

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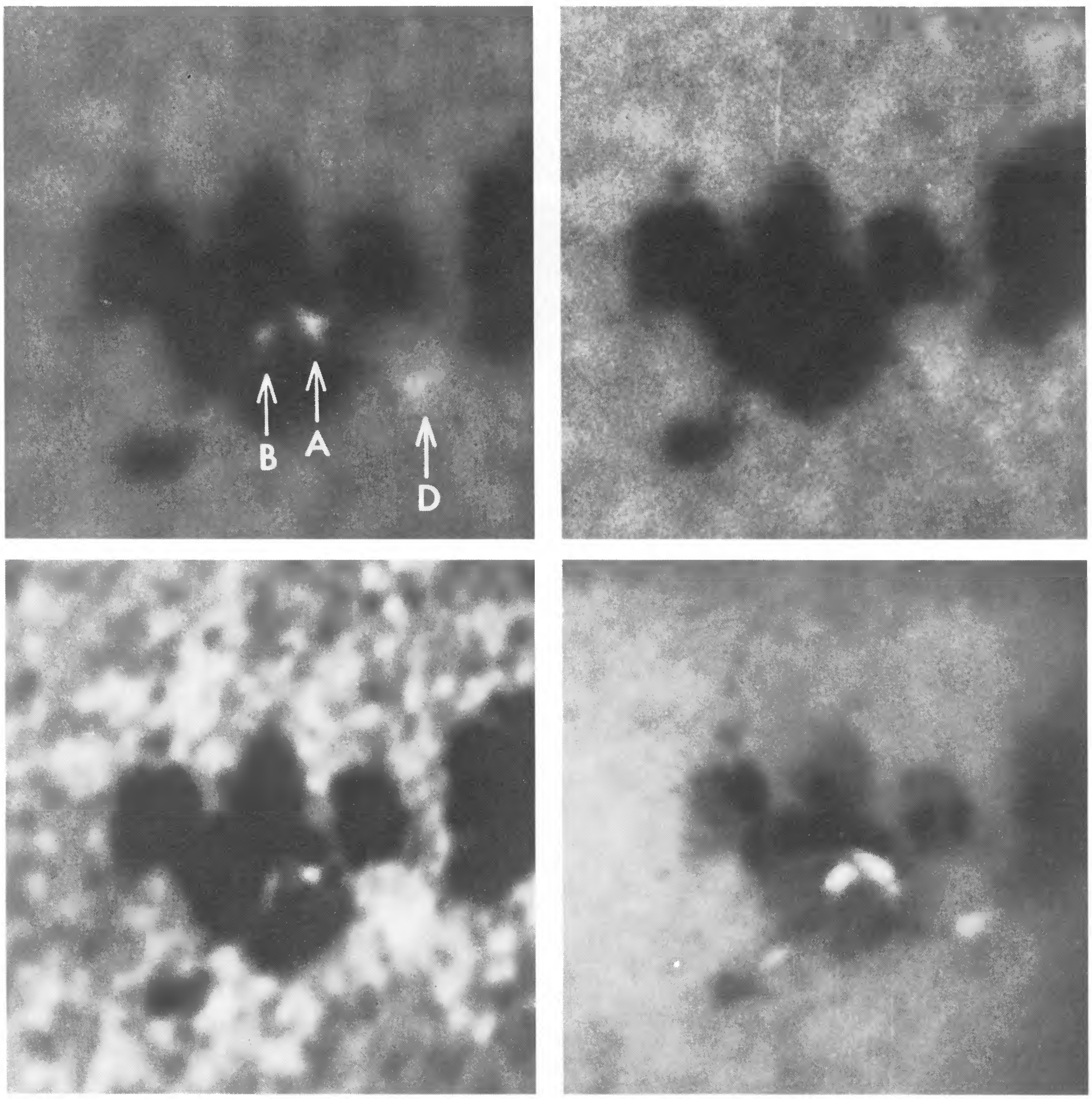

FIG. 1.—The flare at 16:27:00 UT. Clockwise from upper left: 3610 Å (Balmer cont.), 4275 Å, He I D3, and 3862 Å. Kernels A, B, and D are not visible in any of the four continuum bands at wavelengths > 4275 Å (N is top; W is right). D3 and 3862 Å are BBSO photos, all others are from SPO.

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of 1.13 times the photosphere for the 1972 August 7 flare. Kernel D was simultaneous with A and B, but distant from the main neutral line; it resembled point C but was less intense.

X-ray data from the *International Sun-Earth Explorer* (*ISEE*) (kindly furnished by S. Kane) and from the *Solar Maximum Mission* (*SMM*) (kindly furnished by L. W. Acton and K. J. Frost) show a hard X-ray precursor at 16:26:00 UT, an abrupt rise at 16:27:00 UT to a spiky maximum between 16:27:10 and 16:27:45 UT, a decline to a shoulder lasting to 16:29:45 UT followed by decay. Our 10.7 GHz data from the Owens Valley Radio Observatory (OVRO) is similar (see Zirin and Tanaka 1981), while the soft X-rays show a broad peak at 16:28:30 UT followed by a shoulder to 16:31 UT.

The kernels, C and D, were quite different from the early flashes, A and B; they were diffuse and longer lived, while A and B were actually a number of different shorter flashes. The same behavior occurred in the 1972 August 2 (18:38 UT) flare (Zirin and Tanaka 1973) where, after the short-lived flashes, along the neutral line in the impulsive phase there was a long-lived bright point some distance away and a moving wave in the next flare at 20:05 UT. Point D, which moved irregularly about 10,000 km in a minute, was similar to the wave in the second flare of 1972 August 2 (20:05 UT); and point C, which did not move, was similar to a fixed bright kernel in the 1972 August 2 18:38 UT flare. Bright He D3 emission corresponded to all the points of continuum emission and was only 20% more intense at C and D, but was about twice as bright as the blue continuum at kernels A and B. A strong magnetic transient, quite similar in distribution to the He D3 emission (see Zirin and Tanaka 1981), appeared near A and B, and weaker transients appeared at C and D.

Although all the points of emission were easily visible in λ3610 (Bac) and λ3862 (blue continuum), only point C was visible, rather weakly, in the wavelengths above 4000 Å. Emission in λ3862 was barely detectable at 16:27:00 UT but rose rapidly afterward, with kernel D peaking at 16:27:37 UT at 1.7 times the photospheric intensity (intensities are referred to the nearby photospheric intensity at that wavelength). The points A and B, site of several flashes associated with the hard X-ray burst recorded by *SMM*, died down by 16:28:15 UT. Between 16:28:47 and 16:29:17 UT, point C brightened to a peak of 2.1 times the photosphere at 3862 Å and 2.5 times at 3610 Å.

We have measured both peak and integral intensities in the various kernels. Since the SPO data which give us spectral information only cycled through the spectrum once in 90 s, while the flare emission changed rapidly, spectral data must be obtained by comparing simultaneous BBSO and SPO frames. The measured peak intensities of points on the SPO frames are given in Figure 3,

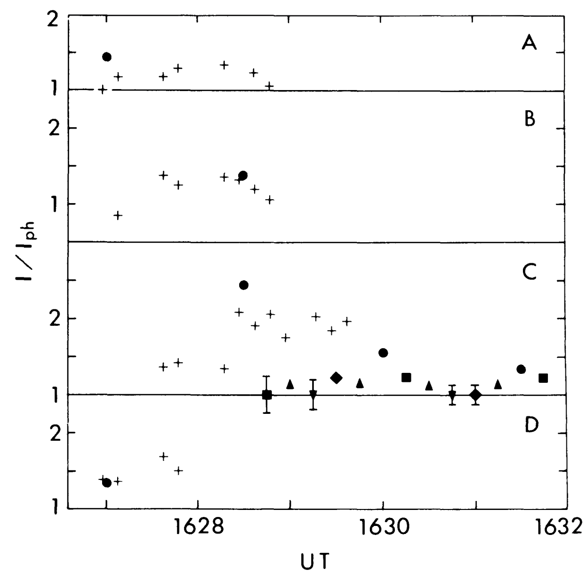

FIG. 3.—Light curves for the four flare kernels. Brightness units are photospheric intensity outside the sunspot at the same wavelength (the background intensities for kernels A and B are about 0.6 and 0.8 times the photosphere, respectively). Symbols indicate λ3862 (*cross*), λ3610 (*circle*), λ4275 (*square*), λ4957 (*triangle, point down*), λ5645 (*triangle, point up*), and λ6203 (*diamond*). Error bars are included for points obtained during exceptionally poor seeing; SPO observations show no detectable emission except where otherwise indicated. No emission is detected in any wavelength after 16:31:45 UT.

along with the simultaneous peak brightness of the same points at λ3862 on the BBSO frame. We have allowed for the higher resolution of the BBSO frames by multiplying the excess of SPO intensities over the background by 1.5; this number comes from a comparison of the measured area of the bright kernel C on simultaneous frames. We assume that Bac and λ3862 emission are cospatial. Unfortunately, the BBSO data were interrupted by clouds from 16:29:37 to 16:36 UT, so comparisons can only be made for earlier times.

The ratio of λ3610 emission to λ3862 emission is about 1.5. This result is independent of the factor 1.5 applied to peak intensities, because integrated intensities are not affected by that correction. There are no published solar data on the Bac/blue continuum ratio, but our result is in good agreement with values in stellar flares (Zirin and Ferland 1981). The ratio of λ3862 to longer continuum wavelengths is between 5 and 10, confirming the conclusion of Zirin (1980) for the 1978 July flare that there is an intense blue continuum of unknown origin below the Ca II K line. In the 1978 July event, the data at long wavelengths were in a line wing, so only a lower limit for the blue/green continuum ratio could be obtained.

The blackbody temperature corresponding to the observed λ3862/λ5645 ratio is 14,000 K. But if the flare were a blackbody at this temperature, the intensity at

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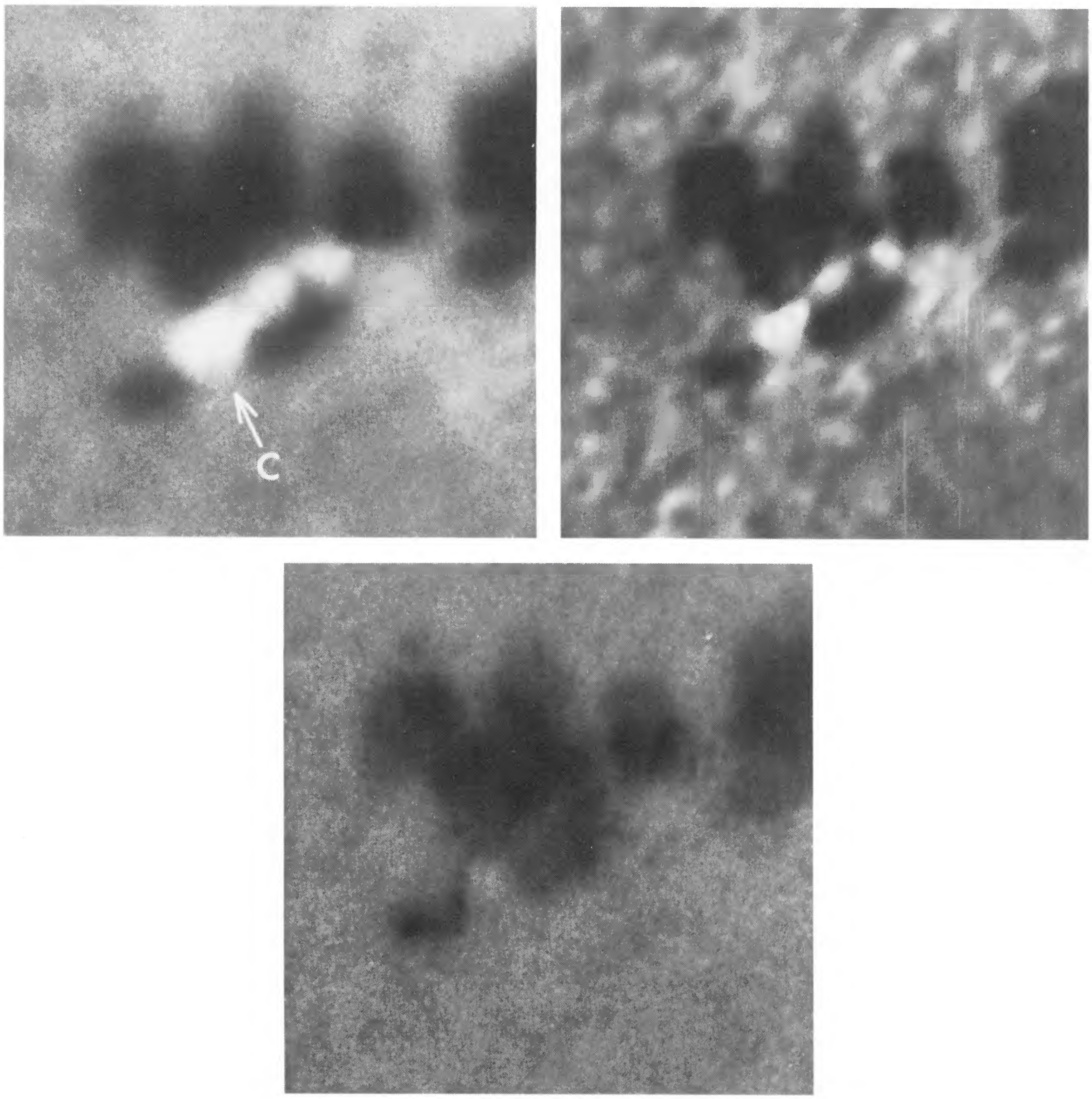

FIG. 2.—The flare at 16:28:30 UT, as observed at 3610 Å, 3862 Å, and 5645 Å. Kernel C alone shows weak emission at wavelengths > 4275 Å. The peak intensity of point C was reached 45 s later, but this is the last time for which we have simultaneous 3610 Å and 3862 Å data.

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λ5645 would more than double, which is not observed. The increase in emissivity at λ3862 alone is easily accounted for by a rise in temperature to 7000 K. Therefore, we must admit the existence of a special opacity below the K line (see § III) which makes the temperature increase in the upper photosphere visible at those wavelengths. Not knowing the spectral properties of the Bac emission, we cannot determine a reliable temperature from the λ3610 data, but the brightness of the Bac can certainly be fit by 7000 K.

The integrated energy emitted in the continuum, including all wavelengths 3000–7000 Å, was about 5×10^{27} ergs s^{-1}.

We find no polarization in any of the SPO broad-band data. Comparison of the simultaneous images shows that the bright λ3610 emission is unpolarized to within the limit (~ 3%) of instrumental sensitivity. For the longer wavelengths, the upper limit is an order of magnitude greater because of the weak signal.

III. DISCUSSION

We have found definite evidence of blue continuum below λ4275, a good upper limit for the polarization in the Balmer continuum, and a continuum peak after the hard X-ray peak and the Hα flash phase associated with an isolated peak in 2.2 MeV and Fe I and Kα.

It has been suggested that linear polarization might be observed in flares if the continuum were a result of synchrotron emission. But Svestka (1976), for example, shows that, if the white light emission were a result of synchrotron emission, the X-ray flux would be enormously greater than observed. Nonetheless, because the white light emission might be excited by proton beams which at least define a preferred direction, it is worth while to look for possible polarization. Unfortunately, our upper limit is best for the Balmer continuum, where recombination picks out slow thermal electrons and the chance of polarization seems remote. But the SPO data do show that there is not substantial polarization in the visible and not even small polarization in the Bac. Of course, synchrotron emission would not give the spectral properties we observe.

Matz *et al.* (1981) presented *SMM* data with the 2.2 MeV neutron-proton capture line beginning between 16:26:45 and 16:29:45 UT in the decay phase showing the highest flux of all. A corresponding peak in Fe I and Kα was reported by Phillips (1981, private communication). The timing is correct to associate the first 2.2 MeV peak with the hard X-ray/radio spike (and the first peak of circular polarization at 10.7 GHz) which peaked at 16:27:15 UT and the second, greater peak (if real) with the continuum brightening at C. At that time there was little hard X-ray emission, but we observed a secondary peak of 10.7 GHz radio emission at OVRO with renewed circular polarization and phase shift corresponding to a shift of the source to point C.

The good coincidence in time of the brightest continuum source with the 2.2 MeV line emission and the obvious existence of blue continuum enable us to be more specific about the source of flare continuum. For a long time it has been clear that electrons cannot penetrate to the level of $\tau = 1$ in the visible continuum (Svestka 1976). Svestka and others have suggested that the energy source for the continuum is protons, and the present data would appear to confirm this. The delay time for the 2.2 MeV line is model dependent but, from the timing of the first peak, cannot exceed 60 s. For 80 s before the second 2.2 MeV peak, the bright spot C was the only visible continuum kernal and, in the absence of a related X-ray spike, must have been excited by the same protons that produced the second 2.2 MeV peak. The strong X-ray burst which peaked at 16:27:30 UT produced the much fainter continuum emission along the neutral line. The hard X-ray and 10.7 GHz data show a shoulder only half the main peak, and the soft X-rays did not peak at this time, nor were they exceptionally strong (to compare with the extraordinary intensity of point C). Calculations by Schatzman (1965) show that 20 MeV protons can easily reach the level in question. Although it is possible that the second peak reported by Matz *et al.* was spurious, there is no question that some agent, not electrons, produced a remarkably bright kernel at point C.

If the blue continuum is a result of helium continuum, as suggested below, it could come from a higher level. The literature (Svestka 1976) indicates that other "white light" flares exhibit the same blue spectrum observed here. The spectral shape of the continuum of the 1972 August 7 flare (Machado and Rust 1974) was similar, showing an increase below 4000 Å.

The blue continuum below 4000 Å is also observed in some stellar flares (Zirin and Ferland 1981) and in quasars and Seyfert galaxies. In the latter the blue continuum is thought to be caused by the merging of higher Balmer lines, but the present data and higher resolution stellar data rule out that explanation for flares, solar or stellar. The source of opacity which makes such continuum visible is unknown; all H^- opacities decrease to the blue. The appearance of the network near the limb can be explained by line blanketing; Sheeley (1969) shows it visible in spectroheliograms in the CN band head at 3883 Å, but not in the continuum window at 3884 Å. In all published flare spectra, the emission lines are too narrow and weak to raise the integrated emission to twice the photospheric intensity. We have not observed the blue continuum at disk center, and several sizeable flares observed there in 1980 November showed no λ3862 emission. The visibility of blue continuum depends on opacity to some extent; we do not know if the same is true of the Balmer continuum.

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REFERENCES

Machado, M. E., and Rust, D. M. 1974, *Solar Phys.*, **38**, 499.
Matz, S. M. *et al.* 1981, *Bull. AAS*, **12**, 910 (paper F14).
Schatzman, E. 1965, in *The Solar Spectrum*, ed. C. de Jager (Dordrecht: Reidel), p. 313.
Sheeley, N. R. 1969, *Solar Phys.*, **9**, 347.
Svestka, Z. 1976, *Solar Flares* (Dordrecht: Reidel).
Zirin, H. 1980, *Ap. J.*, **235**, 618.
Zirin, H., and Ferland, G. 1981, BBSO preprint 192.
Zirin, H., and Tanaka, K. 1973, *Solar Phys.*, **32**, 173.
______. 1981, *Ap. J.*, submitted.

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