Solar flares not producing sudden phase advances

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[1] We present a study of solar flares that do not produce disturbances in the low terrestrial ionosphere, detectable in very low frequency (VLF) low ionosphere propagation as sudden phase advances (SPA). We selected only flares with larger optical H-α importance (equal or larger than 1), occurred near the cycle 22 solar maximum (1987–1989), at times when VLF data were available for long-distance propagation paths entirely illuminated by the Sun. For the 463 optical solar flares selected, we found that 18.8% had no measurable effects on the lower ionosphere. Inversely, all measured SPAs did have a solar counterpart, optical (such a subflare) and/or X-ray fluxes. Among the H-α flares that do not produce measurable disturbances in the low terrestrial ionosphere, there is a surprising selection for events occurred at the solar limbs. On the other hand, the X-ray flux for the H-α flares selected, obtained from GOES for the bands 0.5–4 Å and 1–8 Å exhibited a rather scattered correlation with the SPAs amplitudes. GOES X-rays fluxes for H-α flares not producing SPAs extend over 2–3 orders of magnitude. These results may suggest real physical distinctions between events. Possible explanations suggest the existence of a directional trend for the soft X-ray produced in flares possibly combined with the blockage of ionizing X rays behind the solar limbs. *INDEX TERMS:* 2435 Ionosphere: Ionospheric disturbances; 2479 Ionosphere: Solar radiation and cosmic ray effects; 6929 Radio Science: Ionospheric physics (2409); 7519 Solar Physics, Astrophysics, and Astronomy: Flares; *KEYWORDS:* solar flare effects, sudden ionospheric disturbances, SID, SPA, VLF anomalies, flare soft X rays

1. Introduction

[2] We have known for many decades the daytime low terrestrial ionosphere response to solar emissions. One of the best studied effects is the sudden ionosphere disturbance (SID) detected as very low frequency (VLF) propagation anomalies: the sudden phase advances (SPAs) and sudden enhancements of signal strength (SES) [*Wait*, 1959; *Chilton et al.*, 1963; *Crombie*, 1965].

[3] Earth-ionosphere spherical waveguide models give the best description of long-distance VLF transmission (>2 Mm) [*Wait*, 1959; *Watt and Crogham*, 1967; *Harth*, 1982, and references therein]. The upper boundary of the waveguide, the daytime ionosphere *D* region, is very sensitive to the excess ionizing radiation from solar flares, which produce a net reduction of the waveguide height. Consequently, the VLF signals produced by a distant transmitter, propagating in this waveguide, will exhibit a phase advance. In the *D* region the maximum ion production rate is believed to be due primarily to the 10 keV soft X ray [*Rees*, 1989; *Hargreaves*, 1992, and references therein] which roughly corresponds to the 0.5–4 Å band of the GOES detectors. Phase sensitive receivers detect the VLF signals produced by a number of fixed transmitters at different locations in the world, used for navigation support. High-precision frequency standards, such as atomic clocks, control the VLF receivers, allowing high accuracy in phase advance measurements, depending on the time integration [*Chilton et al.*, 1963; *Crombie*, 1965; *Watt and Crogham*, 1967; *Harth*, 1982, and references therein]. The most common VLF data available are time integrated by tens of seconds producing meaningful readings within a fraction of a microsecond.

[4] However, we have known for a long time that not all solar flares produce SPAs. It has been pointed out by *Arnoldy et al.* [1967] that nearly 10% of the 10–50 keV X-ray enhancements do not produce measurable SID effects. This proportion, if not just a result from sensitivity selection effects, is not negligible. There were no studies to explain the reasons for these uncorrelated solar flares.

[5] In this study we addressed the question of why certain H-α solar flares do not produce enough ionizing radiation to disturb the terrestrial low ionosphere. We analyzed SPAs detected on different long-distance VLF transmissions (NAA, Omega NDAK, Omega Argentina) received by tracking stations at Itapetinga Radio Observatory, Atibaia, SP, Brazil, for the years 1987–1989, near the solar cycle 22 maximum, for which complete revised solar H-α flares listings were available in IAU Quarterly Bulletins on Solar Activity. We obtained the complementary X-ray GOES fluxes from NOAA/SEC/Solar Geophysical Data. However,

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the GOES detectors observe the whole solar disk and therefore the X-ray fluxes are approximately assumed to be associated to the corresponding H-α flares when there are good time coincidences.

2. Flare and SPA Selection (1987–1989)

[6] We initially selected daily time intervals for which there were data available for VLF propagation paths entirely illuminated by the Sun and for which there were confirmed H-α flares monitoring [*International Astronomical Union* (*IAU*), 1987, 1988, 1989]. To avoid lower limit threshold selection effects in H-α flare identification, we have taken only larger flares with reported importance equal or greater than 1. Events identified in the solar disk are classified after two qualitative evaluations (see, e.g., the *Quarterly Bulletins on Solar Activity* ([*IAU*, 1987, 1988, 1989]) and National Oceanic and Atmospheric Administration's *Solar Geophysical Data Reports* (1987, 1988, 1989)): H-α emission area, ranging from S, 1, and 2; and brightness, which can be F (faint), N (normal), and B (bright). We have therefore excluded all medium to small and subflares (classes SF, SN, and SB), selecting only larger optical H-α of class 1 and above.

[7] We considered VLF signals sudden phase advances, SPAs, bigger than 1 μs, above the detection reading limits of about 0.5 μs. The phase advances were approximately normalized for different VLF frequencies and propagation paths distances, converting the measured SPAs from microseconds into degrees per megameter (Mm, of path length) units. We detected nearly 68% of SPAs used in this study on Omega Argentina transmissions at 10.2 and 12.9 kHz, on a 2.8 Mm path length. The most typical SPA observed phase advances on this transmission was of about 5 μs, or about 20°, which correspond to a normalized 7°/Mm. 28% of SPAs were detected on NDAK transmissions, at 13.1 and 13.6 kHz, along a 9.3 Mm path. On these transmissions, the most typical SPA was of about 20 μs (96°), giving a typical normalized 10°/Mm. The remaining 4% SPAs, detected on NAA (24 kHz), on a 7.9 Mm path, were typically of 10 μs (86°), giving typical normalized 11°/Mm.

[8] Another possible selection effect on SPAs detection is the known dependence on the Sun's zenithal angle with respect to the VLF propagation path [*Chilton et al.*, 1963; *Muraoka et al.*, 1977]. The first collection of SPAs obtained in the period 1987–1989 has been plotted against the solar zenith angle at the middle of the propagation path were the event has been detected, as shown in Figure 1. The data in the diagram show some dispersion in events occurrence at different elevation angle intervals but confirm earlier findings of a significant reduction in SPAs detection for large solar zenith angles (>75°). To minimize this effect we excluded from the collection the SPAs measured at solar zenith angles $\geq$70° resulting in 463 events selected for this study.

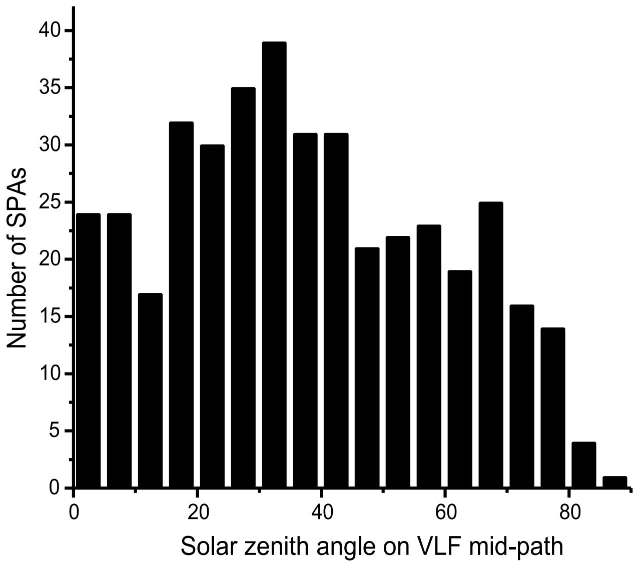

Figure 1. Distribution of SPAs for different solar zenith angles on the VLF propagation midpath.

3. H-α Flare Positions in the Solar Disk

[9] In Figure 2a we show the longitude position in the solar disk for all the optical H-α flares (with importance equal or larger than 1) which have produced SPAs. There is a certain dispersion in the data, with a slight suggestion for a larger SPA-producing flare incidence at intermediate solar longitudes ($\approx$30°–60°) and a clear reduction toward the solar limbs, at longitudes >80°.

[10] In Figure 2b we show the distribution of the optical H-α flares which have not produced SPAs. They correspond to 87 (18.8%) H-α flares, with importance equal or larger than 1, which have not produced any measurable phase anomaly (SPAs) on long-distance VLF propagation paths. This finding provides a surprisingly high number of important H-α flares, which do not ionize the low terrestrial ionosphere, almost twice as much as one earlier suggestion [*Arnoldy et al.*, 1967]. Moreover, Figure 2b shows a clear preference for H-α events (32 out of 87) which do not produce SPAs for the solar limb location, at longitudes >80°, which physical implications will be discussed later.

4. GOES X Rays and SPAs

[11] The soft X-ray fluxes for the H-α flares selected for this study were derived approximately from GOES soft X-ray measurements in the bands 0.5–4 Å and 1–8 Å, published by the NOAA's Solar Geophysical Data Bulletins (1987–1989). However, since the GOES burst detectors observe the full Sun, the flux readings are not highly accurate and do not correspond always and necessarily to the identified H-α flares contribution. Nevertheless, the GOES X-ray data might be useful for qualitative comparisons to the corresponding properties of VLF phase advances with respect to the selected H-α flares.

[12] We show in Figures 3a and 3b, the X-rays peak fluxes for the 0.5–4 Å and 1–8 Å bands corresponding in time to the H-α flares selected. We shall assume that the X-rays originated in the same H-α flaring sites. Although the approximate correlation between the log of X-rays fluxes and SPAs agree qualitatively with the earlier findings obtained for fewer VLF SPA events using the NRL Solrad Satellite [*Kaufmann and Paes de Barros*, 1969; *Muraoka et al.*, 1977], the present results for a bigger collection of events exhibit a much larger dispersion. X-ray flares and

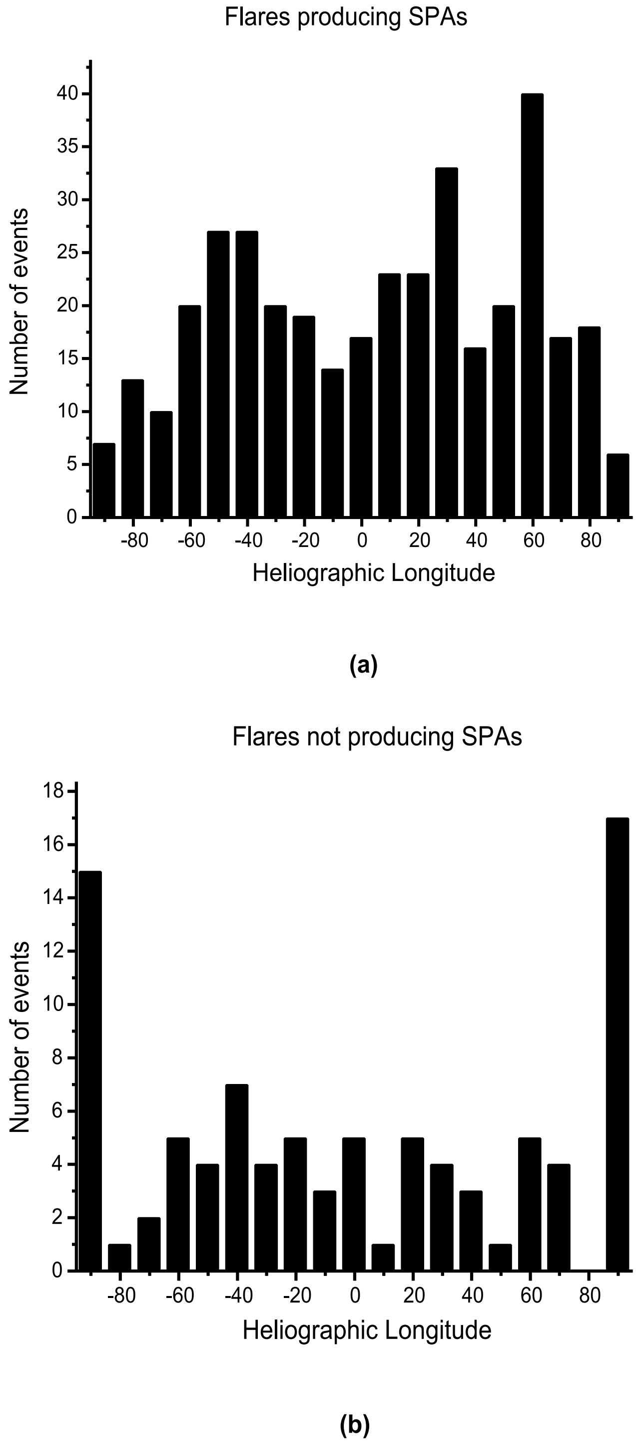

Figure 2. The heliographic longitude distributions of solar H-α flares with importance equal or greater than 1 in the solar disk: (a) flares producing SPAs and (b) flares not producing SPAs.

SPAs follow the approximate relationship $\log(I) = \sim a(\mathrm{SPA}) + b$ where the SPA is in deg/Mm and I in W/m^2. The correlation coefficients for the linear fits are of 53.3% and 59.5% for the 0.5–4 Å and 1–8 Å X-ray bands, respectively. The fit coefficients for the 0.5–4 Å X rays are $a = 6.6 \times 10^2$; $b = -6.3$ and for 1–8 Å are $a = 5.1 \times 10^2$; $b = -5.3$, which are comparable to the coefficients obtained before with X rays measured by NRL Solrad earlier generation of satellites [*Kaufmann and Paes de Barros*, 1969; *Muraoka et al.*, 1977].

[13] The scatter diagrams in Figures 3a and 3b show a wide range of X-ray fluxes for events with no SPA detected (i.e., for which the phase advances were less than 0.5 μs).

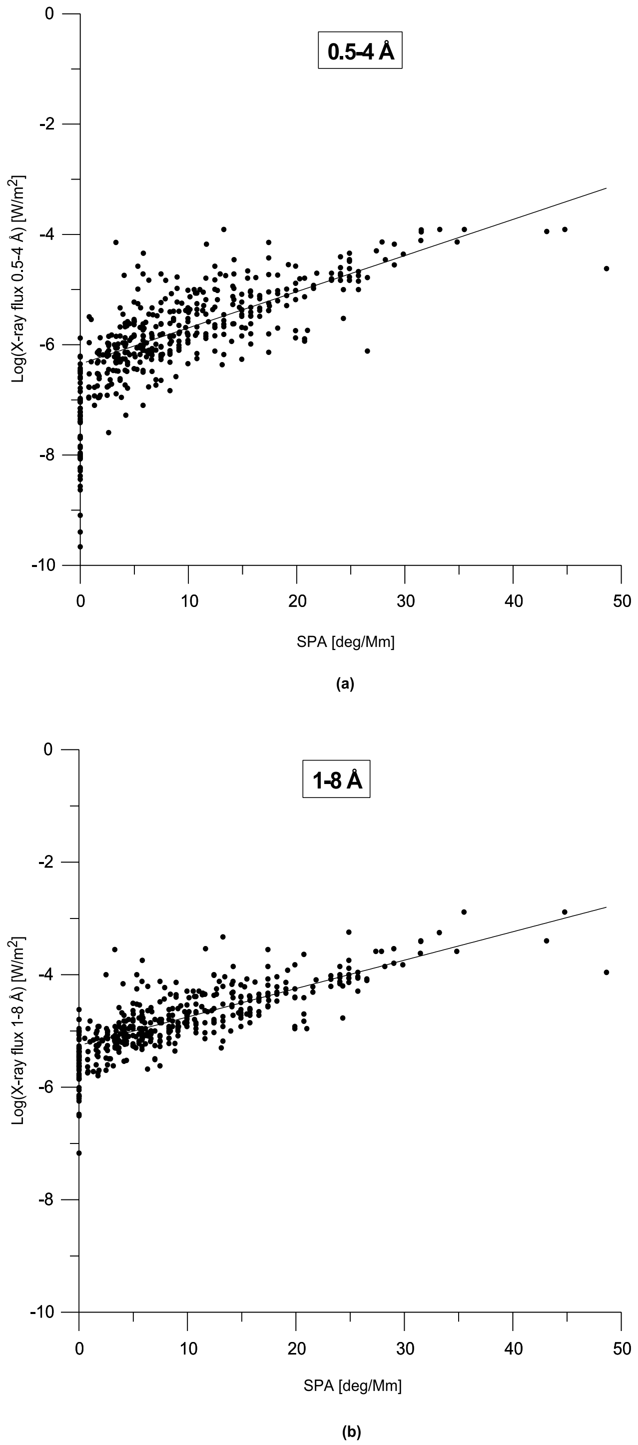

Figure 3. The correlation of VLF SPA phase advances and the log of the GOES soft X-ray fluxes in the bands (a) 0.5–4 Å and (b) 1–8 Å, attributed to the H-α flares selected in 1987–1989.

They correspond to the 87 H-α flares, with importance equal or larger than 1 which have not produced any measurable phase anomaly (SPAs) on long-distance VLF propagation paths.

[14] The X-ray flux level below which there was no SPA detection, extend over nearly three orders of magnitude in the 0.5–4 Å band, and 2 orders of magnitudes in the 1–8 Å band with no clear "threshold" defined. These X-ray fluxes corresponded to H-α flares with importance 1F (22 flares), 1N (48), 1B (15), and 2B (2). On the other hand we found no significant difference in the X-ray flaring region temperatures as derived from the ratio of the fluxes detected in the two bands [*Thomas et al.*, 1985] for flares producing or not producing SPAs.

[15] These results suggest that we cannot easily explain possible real physical distinctions, which may exist between bursts.

5. Conclusions

[16] The analysis of 463 solar H-α flares of larger importance (1 or greater) has shown that 18.8% of them do not produce measurable SPAs on VLF long distance propagation in the lower terrestrial ionosphere. The non-SPAs flares exhibit clear concentrations for events occurring at the solar limbs. The flare associated soft X-ray emissions, approximately derived from GOES detectors, does not show properties distinct from the flares producing and not producing SPAs. GOES fluxes for H-α flares not producing SPAs extend over 2–3 orders of magnitude and a pronounced scattering was found for the log (X-ray flux) versus SPA relationship. These results might be representative of physical distinctions between events at the Sun.

[17] The ionizing emissions may emerge from the Sun within a certain wide cone angle, which directionality effects become more pronounced at the solar limbs. The blockage by the solar limb on the ionizing radiation might also play an important role to account for the observed effect. We suggest that further studies should be done on SPA events together with spatial morphology description of soft X-ray emissions obtained by Yohkoh SXT experiment [*Tsuneta et al.*, 1991].

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