Indian Journal of Radio & Space Physics
Vol 44, September 2015, pp 122-125

Solar cycle variation of coronal green line index

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Received 27 February 2015; revised 29 July 2015; accepted 11 August 2015

During 1966-2008 (solar cycles 20-23), the evolutions of sunspots (Rz) and solar flare index (SF) show similar evolution, i.e. a rising phase, a broad maximum and a declining phase in each cycle. On the other hand, coronal holes are more frequent in the declining phase of each cycle. Hence, the coronal green line index (CG), which represents coronal heating, is expected to be similar to sunspots and solar flare index during the rising and maximum phases of solar cycle but dissimilar in the declining phase. Observations show that this was true, but the excess of CG in the declining phase is small compared to the CG intensities at solar maximum. Thus, the contribution of coronal hole could not be unique or even major one for the large coronal heating. There are many solar parameters which evolve differently from the sunspot numbers. But in the present paper, it is assumed that comparison with sunspot numbers may be a reasonable one.

Keywords: Coronal green line index, Coronal hole heating, Solar flare index, Sunspot
PACS Nos: *96.60.pc*; *96.60.qd*; *96.60.qe*

1 Introduction

Solar corona has very high temperature (several million Kelvin). One mechanism to explain this, namely absorption of Alfven waves[1] emanating from the solar interior and propagating outwards was suggested by Parker[2,3] but discarded by him on the grounds that the waves could not bypass the chromosphere and heat only the corona. Also, the strength of these waves was probably inadequate to create very high temperatures. One of the mechanisms presently accepted for coronal heating relates to solar flares, defined as sudden, rapid and intense variation in brightness. A solar flare occurs when magnetic energy that has built up in the solar atmosphere is suddenly released due to merging of magnetic loops of opposite polarity, causing magnetic annihilation, mostly in the top of the chromosphere and bottom of the corona. Radiation is emitted in a large range, from radio waves at the long wavelength end through optical emission to X-rays and gamma rays at the short wavelength end. The energy released during a flare is typically the order of 10^{27} ergs per second. Large flares can emit up to 10^{32} ergs of energy[4]. Some of this energy is absorbed as kinetic energy in the coronal plasma leading to very high temperatures. A measure of coronal temperatures is the intensity of the coronal green line. The high temperature of the Sun's corona gives it unusual spectral feature, which have been traced to highly ionized iron (Fe-XIV)[5,6] and are identified as transitions from low-lying metastable levels of the ground configuration of highly ionised metals (the green FeXIV line at 5303 Å, but also the red line FeX at 6374 Å).

The coronal green line intensities are used as a measure of the coronal green index. Xanthakis *et al*.[7] attempted to define the intensity of the coronal green line as an integrated index of the solar activity, which can express all photospheric and coronal phenomena of the Sun. The contraction of the low density coronal hole regions and the presence of bright loops during solar maximum provide a theoretical explanation of the mentioned relation.

There is another phenomenon called coronal holes, which are more frequent in the declining phase of sunspot activity. Drs Michael Hahn and Daniel Wolf Savin, research scientists at Columbia University's Astrophysics Laboratory in New York, found evidence that magnetic waves in a polar coronal hole contain enough energy to heat the corona and moreover, they also deposit most of their energy at sufficiently low heights for the heat to spread throughout the corona[8]. The observations help to answer a 70-year-old solar physics conundrum about the unexplained extreme temperature of the Sun's corona known as the coronal heating problem.

For the coronal heating problem, two mechanisms have been proposed, viz. heating by MHD waves or by microflares. The role of the solar flares in the coronal heating is basically true for the transient heating (for a couple of minutes to hours). The sudden heating in the solar flares is basically contributed by the acceleration of non-thermal electrons from the re-connection site to the foot point. These electrons are precipitated in the chromosphere and therefore, heat plasma upto several MK temperature. This is a transient phenomena (not occurring every time). Quiet corona heating (1-2 MK) is explained either by MHD waves or by microflares. Microflares are very copious and can contribute to coronal heating in a more uniform way.

The coronal green line index (coronal index) is a general indicator, which characterizes the presence of long-lived coronal structures and represents the daily irradiance emitted by the green corona (Fe XIV, 530.3 nm)[9,10]. It, thus, gives a better measure of solar-terrestrial effects[10] than sunspot-related indicators (such as sunspot numbers or sunspot areas)[11]. According to Aschwanden[12], the coronal heating mechanism can be divided into different categories:

(i) Conventional (mostly analytical) DC and AC models provide an energy source of non-potential magnetic energy and wave energy in the corona, which can be dissipated on small spatial scales.

(ii) Only refined (mostly numerical) MHD models that include the chromospheres and transition region at their lower boundary show significantly enhanced heating rates near the chromospheric boundary rather than in the coronal part and thus, can explain the observed preferential foot point heating and the possibly resulting upflows and over density of the filled loops. Nevertheless, the inclusion of the chromospheric boundaries is very important in any theoretical or numerical model that addresses the coronal heating problem. The coronal heating problem cannot be solved without including the chromosphere.

(iii) Magnetic reconnection models have classically been applied mainly to flare events, which involve typical plasma temperatures of $T \approx 10\text{–}20$ MK. However, the increasing number of detections of flare like events at lower temperatures of $T \approx 1\text{–}2$ MK in EUV (with SOHO/EIT and TRACE) makes it likely that they may also play a key role in (quasi-steady) heating of active regions, as well as the quiet corona. Detailed quantitative models exist for flares, but to a much lesser extent for quasi-steady heating of the quiet corona.

From this study, it becomes clear that theoretical models of coronal heating need to be refined to render them more consistent with the new observational constraints. Two strategies may be envisioned: (a) the inclusion of the chromospheres and transition region in conventional AC and DC models; and (b) the exploration of magnetic reconnection models at lower heating efficiencies than in solar flares. Because coronal holes and the quiet Sun demand two orders of magnitude less heating than the coronal part that is topologically connected with active regions, the solution of the coronal heating problem has to be focused on the foot point heated, filled, and over dense active region loops.

The present paper is not a detailed review of the coronal heating problem. Therefore, these modeling details are not considered. Also, details about coronal green index are not stated.

Whether the energy from coronal holes is the main source of coronal heating is debatable. But during the declining phase of sunspots, profusion of coronal holes is certainly expected to have some contribution to coronal heating. In that case, coronal green line index in the declining phase should show extra intensities above the sunspot values.

In a recent article, Klimchuk[13] highlighted 10 key aspects of coronal heating that must be understood before one can consider the problem to be solved: (i) all coronal heating is impulsive; (ii) the details of coronal heating matter; (iii) corona is filled with elemental magnetic stands; (iv) corona is densely populated with current sheets; (v) strands must reconnect to prevent an infinite build-up of stress; (vi) Nanoflares repeat with different frequencies; (vii) what is the characteristic magnitude of energy release? (viii) what causes the collective behaviour responsible for loops? (ix) what are the onset conditions for energy release? and (x) chromospheric nanoflares are not a primary source of coronal plasma. Significant progress in solving the coronal heating problem will require coordination of approaches: observational studies, field-aligned hydrodynamic simulations, large-scale and localized three-dimensional magnetohydrodynamic simulations, and possibly also kinetic simulations. There is a unique value to each of these approaches, and the community must strive to coordinate better. Thus, there is lot of uncertainty about the coronal heating problem.

In the present paper, a comparison is made between the 11-year solar cycle variations of sunspots (Rz) and coronal green line index (CG) for the period 1943-2008 (solar cycles 18-23).

2 Data

Data for coronal indices is obtained from the NOAA website ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_CORONA/INDEX/Lomnicky/MONTHLY.PLT, and for sunspots from http://www.ngdc.noaa.gov /nndc/struts/results?t=102827&s=1&d=8,4,9.

3 Plots

Figure 1 shows the plots for yearly values (superposed) of sunspots (Rz) and coronal green line index (CG) for even cycles 18, 20, 22 in the first column

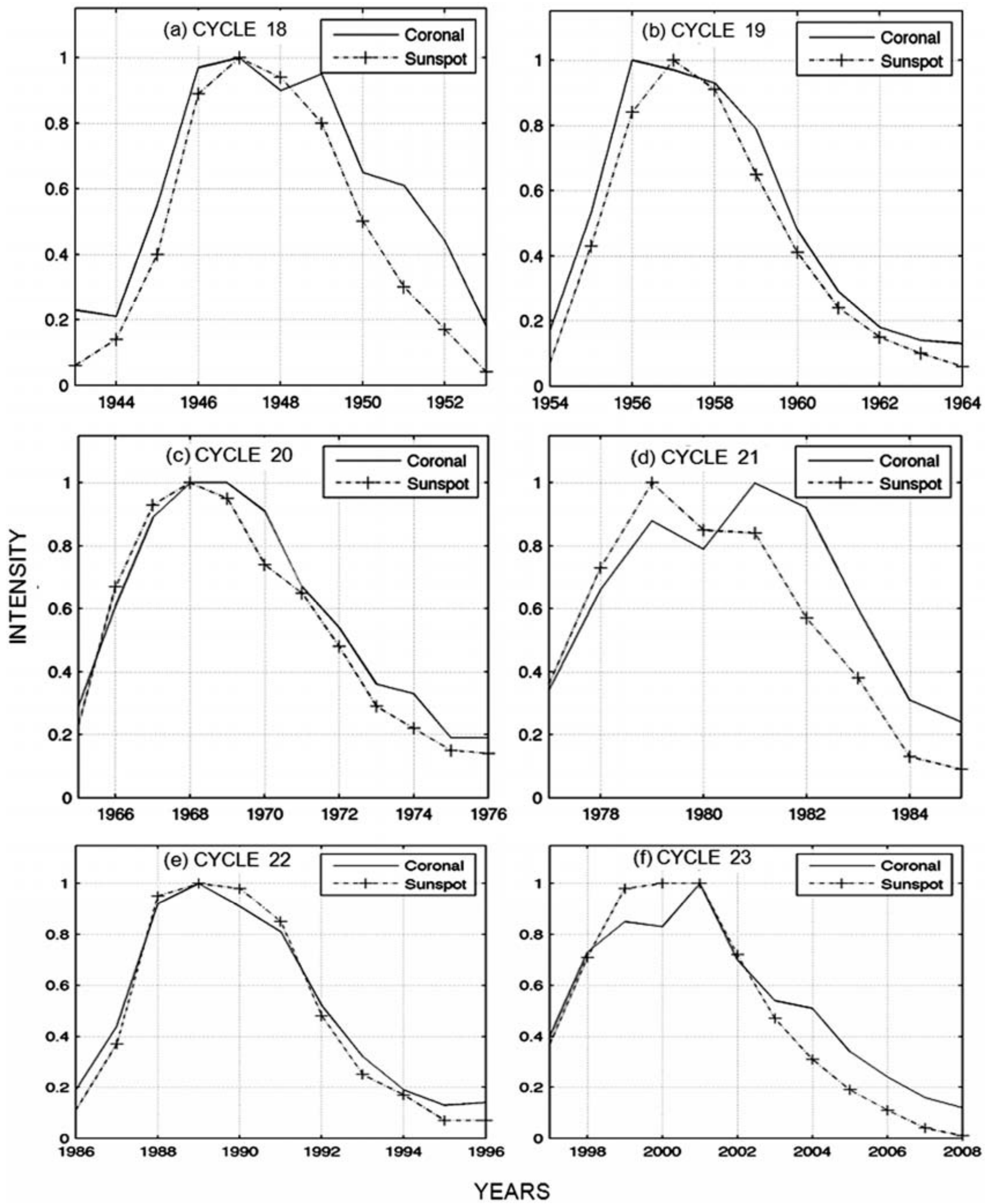

Fig. 1—Plots for yearly values (superposed) of sunspots (Rz) and coronal green line index (CG) for even solar cycles 18, 20, 22 in the first column and odd solar cycles 19, 21, 23 in the second column [In each cycle, the values are normalized as 1.0 for the maximum value of each parameter; thus, all values are in the range 0-1.0]

and odd cycles 19, 21, 23 in the second column. The maximum absolute values of every parameter vary considerably from cycle to cycle. Hence, in each cycle, the values are normalized as 1.0 for the maximum value of each parameter. Thus, all values are in the range 0-1.0. The following may be noted:

(i) For solar cycle 18, there is considerable excess of CG throughout the declining phase. This can be interpreted as contribution due to coronal holes.

(ii) For solar cycle 19, there is almost complete similarity. So, contribution due to coronal holes is negligible.

(iii) For solar cycle 20, there is excess of CG but almost at the end of the declining phase.

(iv) For solar cycle 21, there is excess of CG but almost at the end of the declining phase, similar to solar cycle 20.

(v) For solar cycle 22, there is almost complete similarity. So, contribution due to coronal holes is negligible, similar to solar cycle 19.

(vi) For solar cycle 23, there is excess of CG throughout the declining phase. This can be interpreted as contribution due to coronal holes, similar to solar cycle 18.

(vii) The plots in the left half are not similar, cycle 18 has considerable excess of CG, solar cycle 20 has excess CG but lesser, solar cycle 22 has none.

(viii) The plots in the right half are not similar, solar cycle 19 has no excess of CG, solar cycle 21 has excess but lesser, solar cycle 23 has considerable excess of CG. Thus, there is no 22-year cycle in CG excesses.

4 Discussion and Conclusion

Thus, there is evidence that CG values are considerably larger than Rz values in the declining phases of solar cycles 18 and 23; moderately larger in solar cycles 20 and 21; and no excesses in solar cycles 19 and 22. Also, there is no indication of 22-year cycle. It may be noted, however, that the CG values in the declining phase are much smaller than the CG values near solar maximum. Thus, the corona at sunspot maximum is several times hotter than the corona in the declining phase, indicating that the overall heating of corona is mainly contributed by solar flare effects near sunspot maximum. The contribution to coronal heating due the preponderance of coronal holes during the declining phase is small.

It may be noted that there are several small microflares. One possibility is that the energy is released in many tiny flares, each too small to be observable[14]. Axford & McKenzie[15] suggested that the corona heating is due to high-frequency Alfvén waves generated by micro-flares. Deng et al.[11] have observed discrepancies between the evolutions of coronal index and sunspots, similar to the present results.

Acknowledgement

This work is partially supported by FNDCT, Brazil, under contract FINEP-537/CT.

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