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# Cyclical Variation of the Quiet Corona and Coronal Holes

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**Abstract.** Recent advances in the understanding of the quiet corona and coronal holes are reviewed. The review is based on long-term accumulation of data from eclipse observations, coronagraph observations, helium 10830 Å spectroheliograms, and X-ray observations.

*Key words.* Coronagraphs—solar activity cycle—solar corona—total eclipses—X-ray observations.

## 1. Introduction

The study of the solar cycle variation of the corona requires observational data spanning eleven years or more. The longest record comes from eclipse observations made from time to time over one hundred years, although they give only snap shot data of the corona. The invention of the coronagraph by Lyot in 1930 has made possible persistent observations of the solar corona. Observations of the solar corona from space started in the 1960s, and in 1973-74 the Skylab mission has made, for the first time, high quality and continuous observations of the solar corona in X-rays, EUV, and white light. Since then, the coronagraph (C/P) on board SMM (1980–1989), the soft X-ray telescope (SXT) on Yohkoh (1991-present), EIT and LASCO imagers on SOHO (1995–present), and XUV telescope on TRACE (1998–present) followed. At the same time period of Skylab, helium 10830 Å observations started at Kitt Peak, giving additional information of the corona.

## 2. Eclipse observations

The overall shape of the corona seen at the occasion of total eclipse changes during an activity cycle (Loucif & Koutchmy 1989). The size of polar coronal holes, indicated by the absence of streamers, is largest in activity minimum. The corona is most elliptical in activity minimum, and most circular in activity maximum. This is usually interpreted as follows: there are many streamers in activity maximum, and overlapping of these makes the corona nearly circular, while in activity minimum there are only a few streamers along the equatorial current sheet, making the corona elongated in the equatorial plane. However, recently Gulyaev (1992) and Koomen *et al.* (1998), among others, proposed that the current sheet, which is responsible for an elongated corona in activity minimum, warps or rotates out of the equatorial plane and tends to be seen more and more face-on toward activity maximum. The current sheet seen face-on gives a nearly circular shape of the corona. In the case of the eclipse of 1991 July, the corona looked like an elongated minimum corona, but the orientation of elongation was highly inclined with respect to the equator since we were looking at the inclined current sheet from its edge. This idea of rotating heliospheric current sheet was originally proposed by Saito *et al.* (1978).

## 3. Coronagraphic observations

A Lyot-type coronagraph usually observes at the wavelengths of strong coronal emission lines .The three most frequently used lines and their representative temperatures are:

| | | | |
|---|---|---|---|
| Red line | 6374 Å | Fe X | 1 MK |
| Green line | 5303 Å | Fe XIV | 2 MK |
| Yellow line | 5694 Å | Ca XV | 3.5 MK |

The yellow line is observable only at the occasion of high activity related to flares. The continuum corona (K-corona) due to the Thomson scattering of photospheric light by coronal free electrons can be observed with a K-coronameter, by using the polarization of the K-corona to discriminate it from the sky background.

Fig. 1 shows the latitude distribution of the green line intensity in the form of a butterfly diagram. Superposed dots are the locations of sun spots, namely the conventional sunspot butterfly diagram. The intensity of the green line generally follows the sunspot number (Rusin 1998). However, the latitude distribution of the green-line corona is wider than that of the sunspot belt. In particular, in the activity minimum the corona is bright above the magnetic neutral line surrounding the polar regions. This neutral line migrates from the mid latitude to the pole, with a phase shift of about half a cycle with respect to the migration of the sunspot belt. This picture of the so-called 'extended solar cycle' will be discussed later.

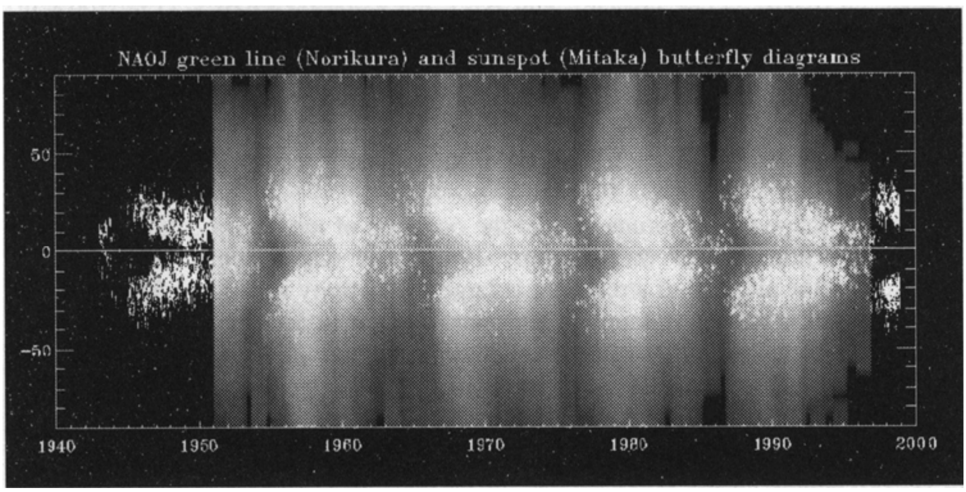


**Figure 1.** The latitude distribution of the coronal green line observed at Norikura in the period of 1951–1997. The superposed dots represent the sunspot distribution observed at Mitaka (1943-1998).

Contrary to the green line intensity, the red line intensity does not clearly follow the sunspot number (Rusin 1998). This is presumably because the 1 MK plasma represented by the red line is cooler than, and therefore is not, the main constituent of the coronal plasma.

The temperature derived from the intensity ratios of green and red lines shows a variation in a solar cycle. The temperature at the poles is highest (1·7 MK) at activity maximum, and lowest (1.3 MK) at activity minimum (Altrock 1998). The distribution of temperature shows an enhancement in high latitudes, above the neutral line encircling the polar regions (Guhathakurta *et al.* 1993), hotter by about 0·5 MK with respect to the temperature of the poles in activity minimum. The increase in temperature at the poles near activity maximum could be due to the approach of the magnetic neutral line toward the poles.

## 4. X-ray observations

The total X-ray flux from the sun varies with the activity cycle. Fig. 2 shows the soft X-ray flux observed by Yohkoh from 1991 to 1999. The total flux at activity maximum is about a factor of 100 larger than that at minimum.

Hara (1996) compared the contributions to the X-ray flux from quiet and active components of the corona. At a certain intensity level, the X-ray emitting structures can be divided into the quiet sun (including coronal holes) and active regions. The total flux comes predominantly from the active region component. The flux variation is due to the change in area occupied by the active regions. The brightness of the active region component, estimated by the ratio between the flux and the area, does not vary significantly within the cycle. The quiet sun component, though it occupies most of the solar surface, is a minor contributor to the total X-ray flux.

The butterfly diagram of the soft X-ray sun observed with Yohkoh (Hara 1996) shows, in addition to the familiar sunspot-related strong emissions, activities in high

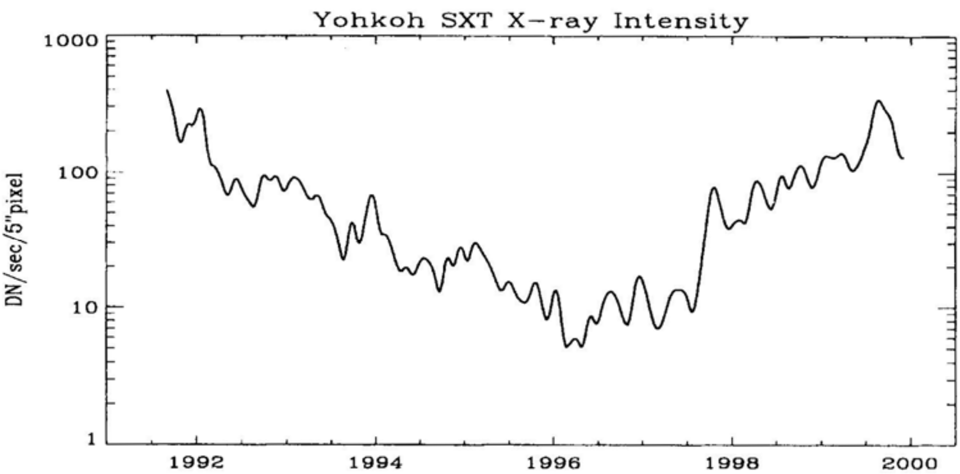


**Figure 2**. Variation of total soft X-ray flux of the sun observed with the soft X-ray telescope of Yohkoh in the period of 1991–1999.

latitudes. Hara (1996) identified that these high-latitude X-ray activities come from the polar ends of coronal large-scale X-ray loops. Probably they can also be explained as the enhanced emission above the magnetic neutral line encircling the poles.

The relation between the activity in the sunspot belt and that of high latitude regions has attracted attention and is termed as 'the extended solar cycle'. Here the meaning of 'extended' needs some clarification. At any point on the sun, the variation of, say, magnetic field strength shows a periodicity of eleven years. If the activity is created by a sub-surface flux tube that migrates toward the equator in the course of the activity cycle, there may exist two or more main flux tubes in the Sun. This is generally the case, since sunspots of the new cycle in mid latitudes and those of the old cycle near the equator coexist in activity minimum.

High latitude activities, which show migration toward the poles, may originate from the poloidal component of the magnetic field, as predicted by the dynamo theory. Since the poloidal field is the seed for the stronger, toroidal magnetic field that produces the sunspot belt later, the beginning of a particular cycle may be traced back to the poloidal component (polar fields) of the previous cycle. The predecessors known so far are; coronal emissions, prominences, torsional oscillations, high-latitude ephemeral regions, and so on.

## 5. Coronal holes

Coronal holes, dark regions in the corona formed where magnetic fields are open to the interplanetary space, have been studied by using X-ray and helium 10830 Å data. The helium 10830 Å absorption is due to the triplet helium whose ground level is 19·7 eV above the ground state, and is believed to be created by the photoionization by the XUV photons from the corona. Therefore the helium 10830 Å spectro-heliograms generally mirror the X-ray images.

X-ray observations were intermittent up to the launch of Yohkoh, which is in operation for more than eight years now. A unique data set of helium 10830 Å spectroheliograms obtained at Kitt Peak since the 1970s provides a proxy to the X-ray corona, with continuity and time span superior to X-ray observations.

The rotation rate of coronal holes has been studied based on the helium 10830 Å spectroheliograms by Navarro-Peralta & Sanchez-Ibarra (1994), and by Insley *et al.* (1995). These authors divided the coronal holes into two classes: (a) equatorward extensions of polar coronal holes (in short, polar holes), and (b) isolated equatorial coronal holes (in short, equatorial holes). At activity maximum the equatorial holes dominate, while at activity minimum the polar holes dominate. This variation of fractional contributions from the two classes during an activity cycle makes it difficult to unambiguously derive the evolution of the differential rotation of coronal holes in an activity cycle. Therefore, Insley *et al.* (1995) only discussed the differential rotation averaged over the cycle, and questioned the results of Navarro-Peralta & Sanchez-Ibarra (1994) who presented the activity-phase dependence of differential rotation.

The equatorial holes migrate toward the equator as the sunspots do, and are interpreted to be phenomena related to active regions. The differential rotation of equatorial holes can be fitted by a quadratic function of $[\cos(\text{latitude})]^2$. The degree of differential rotation for these holes is not as large as for sunspots, but is not negligible as in rigid rotation either. For polar holes, fitting by a quadratic function of $[\cos(\text{latitude})]^2$ gives an almost rigid rotation, but the residuals are quite large and the fitting may not be justified. This character of the rotation of polar holes seems to conform with the theory of Wang *et al.* (1996), in that the holes or open field regions form by a balance of magnetic flux, and bear no definitive relationship with the motion of the surface where the flux originates.

## 6. X-ray bright points

X-ray bright points (XBPs) are small regions ($5–20 \times 10^4$ km) in X-ray images. XBPs can also be identified in helium 10830 Å heliograms as dark points. Part of XBPs originate from ephemeral regions (short-lived, small magnetic bipolar regions), but they also form where two patches of opposite magnetic polarities come across.

Earlier results by Skylab and rocket experiments (Davis 1988) showed that the number of XBPs varies in anti-phase with activity cycle. Since ephemeral regions vary in phase with sunspot numbers, a significant fraction of XBPs do not come from ephemeral regions. Now it is thought that XBPs predominantly form in quiet, mixed polarity regions where opposite polarity patches come across. Such mixed polarity areas are more numerous in activity minimum.

Since XBPs are small and relatively faint objects, their detectability will depend on the level of background X-ray emission, which also varies with the activity cycle. Therefore, Nakakubo & Hara (1999) re-examined the XBP number counts by taking care of different background levels. Their results are shown in Figs. 3 and 4. Fig. 3

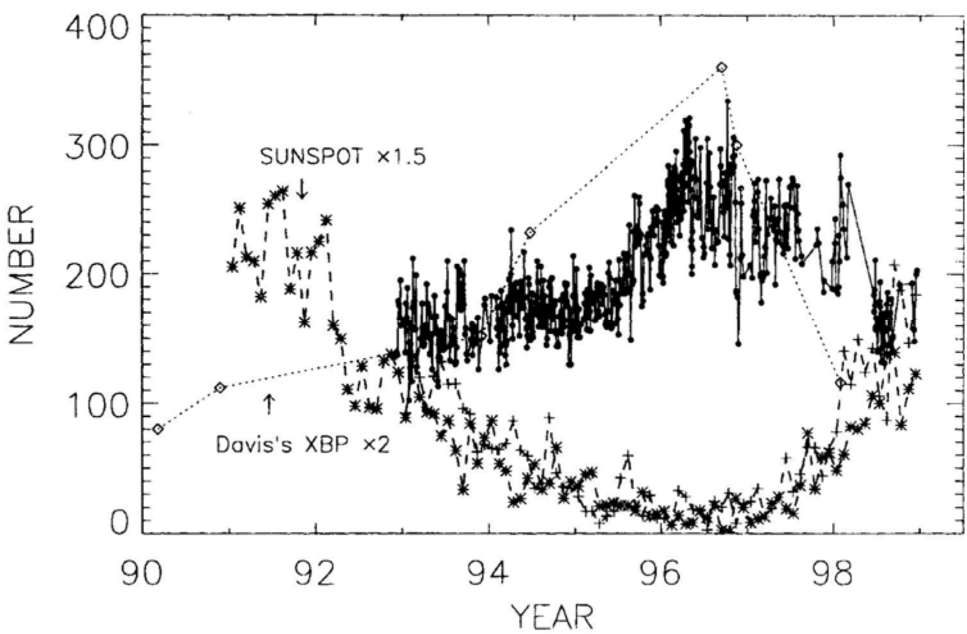


**Figure 3.** Variation of the number of XBPs observed by Yohkoh in the period of 1991-1998. The earlier results of Davis (1988) and the sunspot relative numbers are superposed at the same phases of the activity cycle. (After Nakakubo and Hara 1999).

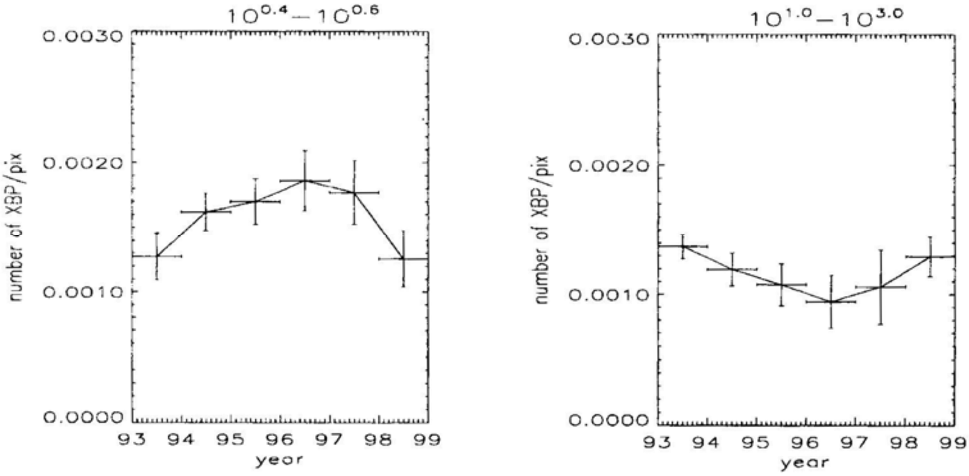


**Figure 4.** The number of XBPs in low (left) and high (right) background levels (Nakakubo & Hara 1999).

shows the total number of XBPs they detected as a function of time. Also plotted are the earlier results by Davis (1988) shifted in time so as to fit into the same activity cycle phase. Their study confirmed the variation of XBP counts to be in anti-phase with the activity cycle. However, it turned out that the situation is not so straightforward. Fig. 4 shows the number of XBPs in regions of low and high background levels. The number of XBPs found in low-background regions are larger at activity minimum (namely, anti-phase with sunspot number), but XBPs found in high-background regions vary in phase with the sunspot number.

XBPs found in high-background regions are intrinsically bright XBPs, while XBPs found in low-background regions, in principle, can include both bright and faint XBPs. However, Fig. 4 indicates that, in regions of low background levels, there are very few XBPs that are bright. Bright XBPs which vary in phase with activity cycle may be a smaller end of active region spectrum, or ephemeral regions, and they tend to form in regions of high X-ray background (presumably in regions of strong magnetic fields). Faint XBPs make another class of objects, e.g. magnetic pairs in mixed polarity regions.

## 7. Final remarks

The orbital life of Yohkoh is estimated to be beyond this activity maximum, and Yohkoh will complete observations over a full solar cycle. GOES Solar X-ray Imager (SXI) of NOAA, planned to commence in 2000, will establish continuous monitoring of the solar corona and will provide valuable data base of the solar activity, more so compared with the GOES X-ray flux.

For ground-based observations, it is welcome that the initiative of SOLIS (Keller, in this issue) at U.S. National Solar Observatory has been funded. A similar plan is being developed in Japan (Sakurai 1998). Let me point out that the time scale of the solar activity is long compared to human cycle. Persistent observations are therefore necessary, and no quick solution is generally possible. We all have to transfer this endeavor generation after generation, in order to clarify the mechanism of solar activity cycle.

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## References

Altrock, R. 1998, in *Synoptic Solar Physics*, (ed.) K. S. Balasubramaniam *et al*., ASP Conf. Ser. **140**, (San Francisco: Astron. Soc. of the Pacific), 339.
Davis, J. 1988, *Solar Phys*., **88**, 337.
Guhathakurta, M., Fisher, R. R., Altrock, R. C. 1993, *Astrophys. J. Letters*, **414**, L145.
Gulyaev, R. A. 1992, *Solar Phys*., **142**, 213.
Hara, H. 1996, in *Magnetodynamic Phenomena in the Solar Atmosphere*, (ed.) Y. Uchida *et al*., (Dordrecht: Kluwer Academic Publishers), 321.
Insley, J. E., Moore, V., Harrison, R. A. 1995, *Solar Phys*., **160**, 1.
Koomen, M. J., Howard, R. A., Michels, D. J. 1998, *Solar Phys*., **180**, 247.
Loucif, M. L., Koutchmy, S. 1989, *Astron. Astrophys. Suppl*, **77**, 45.
Nakakubo, K., Hara, H. 1999, in *Explosive Phenomena in Solar and Space Plasmas*, (ed.) T. Kosugi *et al*., (Japan: The Institute of Space and Astronautical Science), 57.
Navarro-Peralta, P., Sanchez-Ibarra, A. 1994, *Solar Phys*., **153**, 169.
Rusin, V. 1998, in *Synoptic Solar Physics*, (ed.) K. S. Balasubramaniam *et al.,* ASP Conf. Ser. **140**, (San Francisco: Astron. Soc. of the Pacific), 353.
Saito, T, Sakurai, T, Yumoto, K. 1978, *Planet. Sp. Sci*., **26**, 413.
Sakurai, T. 1998, in *Synoptic Solar Physics*, (ed.) K. S. Balasubramaniam *et al.,* ASP Conf. Ser. **140**, (San Francisco: Astron. Soc. of the Pacific), 483.
Wang, Y. M., Hawley, S. H., Sheeley, N. R., Jr. 1996, *Science*, **271**, 464.