Abstract

In this thesis the search for any solar variable showing a cyclic behaviour in the Debrecen Photoheliographic Data (DPD) is presented. DPD is a detailed sunspot catalogue that has not been explored in this way before. The method used is to test parameters included, or calculated out of the given ones in the DPD and plotting the monthly averages with the standard error. Fluctuations present, reveal themselves as periodic curves.

In our analyses the umbra-penumbra area ratio is found to vary in a quasi-biennial manner. The amplitude of the periodicity decreases with increasing size of sunspots but seems to be independent of, e.g., the complexness and age of sunspot groups.

Periodicity analyses of the phenomenon show that the variation has a period that may vary from 1.5 to 3 years or more during the solar cycle.

Preface

When I started my university studies four and a half years ago, the diploma work seemed as distant as the Sun, but time has brought me along quickly. This master thesis contains my last efforts at the Master of Science Programme in Space Engineering at the Luleå University of Technology (LTU) in Sweden.

This preface does not only appear in my thesis but also in the thesis *Solar Mid-Term Periodicities*, written by Johan Kero. We have composed the preface together since we, both being students at the same study programme, have accomplished our diploma work in close collaboration. Our research has been carried out at the Heliophysical Observatory of the Hungarian Academy of Sciences, in the city of Debrecen, Hungary, where we have spent five months during the autumn of 2002. Already during the first months of our analyses, we discovered something interesting enough about sunspots to deserve full-time concern from the both of us during the rest of our stay. To satisfy the demand of two separate reports from our home institution at LTU, our investigations are divided into two self-reliant parts, compiled to be digestible on their own. For a complete overview, the interested reader is advised to read both theses.

We would first of all like to thank our supervisor András Ludmány at the Heliophysical Observatory for his engagement, help and encouragement during the course of our work. Also Tünde Baranyi has been a great help, taking her time to look at new results and trying to interpret them. Without the help of György Mező, with his experience and patience opening doors to methods and software of which we did not have previous knowledge, the computations would have been much slower. All three of them have helped us with valuable ideas and discussions making our work interesting and fun.

We would also like to express our gratitude to László Tóth for taking active part in making our stay at the Heliophysical Observatory unforgettable.

Sverker Fredriksson and Björn Graneli have been our allies at LTU, encouraging and assisting us with the arrangements before we left for Hungary and always eager to help and answer questions during our stay abroad.

This research work has been financed by long-term scholarships from the Hungarian Ministry of Education and support from Ångpanneföreningen's Research Foundation. Our journey to Hungary has been funded by travel scholarships from the Seth M. Kempe Foundation.

The content of this thesis has been partly presented at two separate occasions in Hungary. One was a talk at the 30^{th} National Ionospheric and Magnetospheric Seminar in Tihany, November 11-13, 2002, the other a one-hour seminar at the Astronomical Department at the Eötvös Loránd University in Budapest, November 20, 2002.

Contents

1 Introduction

Our nearest star, the Sun, is very interesting not the least because of its great influence on life here on Earth. Visible features that are relatively easy to observe are sunspots, tempting scientists around the world to toil at their telescopes in search for better understanding of the heart of our solar system.

During my diploma work at the Heliophysical Observatory in Debrecen, Hungary, I have together with Johan Kero found a new feature in the behaviour of sunspots that has not been seen before. The umbra-penumbra area ratio of sunspots has interested scientists before, but none has detected the quasi-biennial fluctuation of this parameter, found by analyses based on the Debrecen Photoheliographic Data (DPD), a detailed catalogue of the sunspot activity.

This thesis gives a complete description of our analyses, beginning with an introduction to sunspot physics (Section 2) followed by a presentation of the DPD containing information about the instruments used, measuring techniques and catalogue structure (Section 3). After some words about other well-known sunspot databases in the world, Section 5 deals with earlier investigations on related subjects. Sections 6 summarizes our task, which was to search any solar photospheric features showing a periodicity present in the DPD, and method of investigation of our diploma work.

The results regarding the umbra and penumbra areas for sunspot groups and the already mentioned quasi-biennial periodicity of the umbra-penumbra area ratio for mainly sunspots, but also for sunspot groups, can be found in Sections 7 and 8 respectively. Period analyses of this phenomenon can be found in Section 9.

The final section, Section 10, reveals the future of the DPD and also the work we have concluded. Though the last chapter in this thesis, our work did not end at that point. When finished with our data analyses, an investigation on some ideas of possible physical interpretations began and this can be found, together with a wide survey of other solar mid-term periodicities, in the thesis of J. Kero [Ke03].

2 Introduction to Sunspot Physics

The striking visible features of sunspots are the dark central umbra and a lighter outer penumbra. This has been known for a very long time. The Egyptians, for example, were probably aware of sunspots already at their time since their sign for the Sun, which we still use today, is a circle with a dot in the middle, i.e., $\odot$. Indeed, very large single sunspots or more often compact sunspot groups are visible to the naked eye, through an appropriate filter of course. The Egyptians probably had good opportunities to see sunspots during, e.g., sand storms. A suitably thick cloud cover or heavy smoke from a fire are other natural filters more common here in Europe.

J. Fabricius, G. Galilei and C. Scheiner made the first telescopic observations of the Sun in the year of 1611. Engravings made during the 17th century show that the observations of that time were already detailed enough to enable distinction between the umbra and the penumbra. The umbra and the penumbra of sunspots being situated deeper than the surrounding photosphere like a saucer, termed the Wilson depression, was discovered during the next century, in 1769 to be precise. The penumbral filaments were revealed in 1801 by W. Herschel [Pr84]. Observations of the latter are front-page news still today because of the successful first half-year of the Swedish 1-m Solar Telescope on La Palma, Canary Islands and its outstanding high-resolution pictures where the filaments can be seen to consist of dark cores inside lighter outer shells [Sh02].

2.1 The Structure of the Photosphere

The photosphere is the outer surface of the Sun as seen in white light, but being entirely gaseous, the Sun has no solid surface. The word photosphere means the sphere in which sunlight originates and comes from the Greek 'photos' for light. The photosphere is extremely thin and is situated at the top of the Sun's convective zone. It is easier to study the photosphere than the unseen zones below and the transparent and variable layers above.

The photosphere is covered with a small-scale velocity pattern known as granulation, and large-scale ones called mesogranulation and supergranulation.

2.1.1 The Granulation

The photosphere is not uniformly bright, nor is it still. The Sun's surface at the photospheric level is completely covered by irregularly polygonally shaped granules, as seen in Figure 1.

The granules are bright with dark, narrow lines in-between. The granules are convective overshoots of the centre of which hot plasma is rising (0.4 km/s) from the Sun's

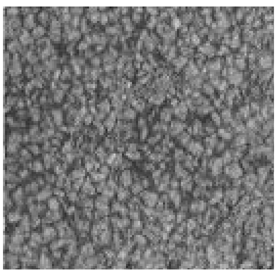

Figure 1: *The granular structure of the photosphere.*

interior, then spreading horizontally (0.25 km/s). At the intergranular boundaries at the edges of the cells, cool material is falling.

The diameter of the granules are typically 700 to 1500 km, corresponding to an angular size of 1 to 2 arcseconds. The mean distance between the cells is about 1800 km, and their mean lifetime is circa 8 minutes.

2.1.2 The Mesogranulation

The mesogranulation is very difficult to detect and is therefore less well-known than the granulation and the supergranulation. Typical sizes of the mesogranules are 5 000 to 10 000 km. The characteristic speed in both the vertical and horizontal direction is about 60 m/s.

2.1.3 The Supergranulation

There is also a much larger scale pattern than the granulation, namely the supergranulation. The supergranulation gives rise to a network of irregularly shaped cells, with diameters ranging from 20 000 to 54 000 km and magnetic fields concentrated at their boundaries. They are made up of plasma rising in the centre (0.1 km/s) and continuing horizontally outward (0.3 - 0.4 km/s) to descend at the rims (0.1 - 0.2 km/s) of the supergranules.

All these velocities are difficult to sense, but the fastest winds in the most severe hurricanes here on Earth have a velocity of 0.1 km/s.

[Fo90] [La00] [Ni82] [Pr84] [Zi88]

2.2 The Solar Cycle

The number of sunspots visible on the solar disc varies in a periodic way, and this 11-year cyclic behaviour of solar activity was discovered in 1843 by H. Schwabe [Fo90]. The state of the solar cycle is given by the relative sunspot number defined as

$$R = K \cdot (10g + f), \tag{1}$$

where g is the observed number of groups, f the observed number of sunspots, and K is a correction factor (typically 0.6), different for different observatories allowing for varying sizes of telescopes, atmospheric conditions and relative enthusiasm of the observer making the counts [Zi88]. This formula was introduced in 1848 by the Swiss astronomer J. R. Wolf [Pr84] as a measure of solar activity. It is therefore also referred to as the Wolf number.

The solar cycle is not exactly 11 years but varies. The cycle rises from minimum to maximum faster than it declines to minimum again. The average time between two maxima varies from 7.3 to 17.1 years and between minima from 9.0 to 13.6 years [Pr84].

During activity minimum the number of sunspots on the Sun is low compared to the huge amount of spots that are often observed during maximum. Sunspots are most often located between the equator and a latitude of $\pm$ 35°. In the beginning of a solar cycle sunspots appear on higher latitudes, but the highest active latitude drifts towards the equator as the solar cycle elapses. The average latitude being dependent on the phase of the solar cycle was first detected in 1859 by R. Carrington [Fo90].

Around 97% of all leading spots of bipolar sunspot groups have the same polarity throughout the solar cycle, but with opposite signs on both hemispheres. With the leading spot, the west spot is meant, which leads in the solar rotation and the east spot is denoted as following. The polarity of the sun reverses at about solar maximum, forming a 22-year cycle called the Hale cycle.

An interesting magnetic feature is that the magnetic axis of bipolar sunspot groups is inclined in such a way that the leading spot is closer to the equator than the following ones. [Fo90] [Pr84] [Ze98]

2.3 Descriptive Introduction to Sunspots

Regions with high magnetic activity are called active regions, and it is within these that sunspots most often arise. Sunspots observed in white-light consist typically of a darker, inner region called umbra surrounded by a lighter penumbra. The reason for the sunspots being darker than the surrounding photosphere is that they are cooler. There is a wide variety of sunspot structures. Sunspots are irregular in shape and only very seldom circular, if ever, sometimes an umbra even lacks a penumbra or vice versa. Umbra diameter sizes range from about 2 000 km to far above 20 000 km.

Less dark features without a penumbra and smaller than about 2 500 km in diameter are termed pores. These have much shorter lifetimes than spots, about a few tens of minutes. The sunspots live from a couple of hours to weeks.

A granulation structure similar to the photospheric one, but in smaller scale, can be observed within the umbra area. The penumbra consists of penumbral filaments, which, in turn, consist of dark cores inside lighter outer shells.

Sunspots occur most frequently in groups, which can have different characteristics. The Mt. Wilson magnetic classification of sunspots, or rather sunspot groups, was introduced in 1919 and is summarized in Table 1. [Fo90] [Pr84] [Zi88]

Sunspot Class	**Characteristics**
α	A single, dominant spot
β	A pair of dominant spots of opposite polarity
γ	Complex groups with irregular distributions of polarities
$\beta\gamma$	Bipolar groups with no marked north-south inversion line
δ	Umbrae with opposite polarity in a single penumbra

Table 1: *Table of the Mt. Wilson magnetic classification of sunspots. [Zi88]*

2.4 Sunspots as Described by Magnetic Flux Tubes

The knowledge of the structure of sunspots is in a sense not more certain than the assumptions one can make of the structure of a tree by looking at the tree top from above. The leaves and branches hide the underlying stem from direct inspection. Several theoretical attempts have been made to describe the sunspot phenomenon, but it is still not possible to distinguish right from wrong. Different models are used in different contexts.

2.4.1 Simplified Description of Sunspot Formation

Deep in the convective zone the kinetic energy density of the plasma convective motions is much higher than the magnetic energy density,

$$\frac{\rho \cdot U^2}{2} \gg \frac{B^2}{2\mu}, \tag{2}$$

where ρ is the plasma mass density, U is the characteristic speed, B the magnetic field strength and μ the magnetic permeability. Furthermore the magnetic Reynold's number R_m can be much larger than unity,

$$R_m = \frac{U \cdot L}{\eta} \gg 1 \tag{3}$$

where L is the characteristic length scale and η is the magnetic diffusivity. In these cases the magnetic field lines behave as if they were frozen into the plasma. They move with it and can be stretched and wound up by the plasma motions. These processes continue until the magnetic field lines are stretched so much that the magnetic energy density exceeds the kinetic energy density or the local magnetic Reynold's number decreases to an order of unity.

Many magnetic phenomena of the Sun, such as the overall structure of sunspots and prominences, can be described by magnetohydrostatic equations since they appear stationary on time-scales comparable to the Alfvén travel time, τ_A. The Alfvén travel time is given by

$$\tau_A = L \cdot \frac{1}{v_A} = L \cdot \frac{\sqrt{\mu \cdot \rho_0}}{B_0}, \tag{4}$$

where L once again is the characteristic length scale of the phenomenon, v_A the Alfvén velocity, ρ_0 and B_0 are typical values of the plasma density and the magnetic field strength. The characteristics of a magnetic flux tube in hydrostatic pressure equilibrium with its surroundings are governed by

$$\frac{k_B \cdot T_e \cdot \rho_e}{m_e} = \frac{k_B \cdot T_i \cdot \rho_i}{m_i} + \frac{B_i^2}{2\mu}, \tag{5}$$

where k_B is Boltzmann's constant, T the temperature, ρ the density, m the mean particle mass and B the magnetic field strength, all with indices e and i corresponding to external and internal properties of the flux tube. The magnetic field strength outside flux tubes is low enough for the external magnetic pressure to be neglected in comparison with the dominating plasma gas pressure, appearing alone on the left-hand side of Equation (5). This is not the case inside flux tubes where the contributions from the magnetic pressure, given by the second term on the right-hand side of Equation (5), are significant. The flux tube will hereby due to equilibrium conditions have an internal density and temperature lower than its surroundings since the external gas pressure on the left-hand side of Equation (5) is balanced by the sum of the internal gas pressure and the internal magnetic pressure on the right-hand side.

If the flux tube has lower density than its surroundings, it will start rising due to gravitational forces, as illustrated in Figure 2.

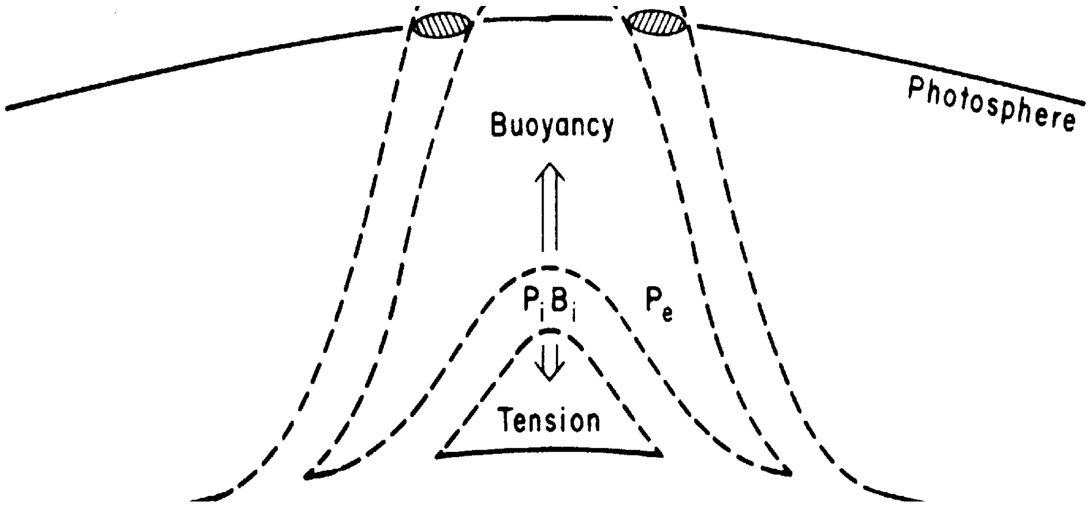

Figure 2: *Schematic sketch of emerging flux tube [Pr84]. Where the Ω-shaped flux tube penetrates the photospheric surface, sunspots are seen having the characteristic temperature deficiency and excess of magnetic field strength compared to the surrounding photosphere.*

The rising process of flux tubes can continue as long as the buoyancy forces on the left-hand side of Equation (6) are larger than the restoring magnetic tension on the right-hand side, caused by the curvature of the field lines,

$$(\rho_e - \rho_i) \cdot g > \frac{B_i^2}{\mu \cdot d}, \tag{6}$$

where g is the local gravitational constant and d is the distance between the footprints of the flux tube in the convective zone. The magnetic field strength of the flux tube decreases as the tube reaches the photospheric surface. There the flux tube, still considered to be in horizontal equilibrium, is allowed to fan out because of the with height decreasing external temperature. Depending on the distance between the footprints of the flux tube, the vertically rising tube can decelerate to an equilibrium where the buoyancy force equals the magnetic tension force, since the latter is a function of the radius of curvature. Where the flux tube penetrates the visible photospheric surface, sunspots are seen, having the characteristics of the flux tube: a temperature deficit and an excess of magnetic field strength compared to the surrounding plasma.

2.4.2 Monolithic and Cluster Models

There are basically three different theoretical models for how sunspots are formed by flux tubes and maintained stable in the photosphere. The classical picture is that a sunspot is formed by a single magnetic flux tube, which makes out the base of the magnetohydrostatic and magnetoconvective models. These models are called monolithic and one expects that the vertical dimensions of a sunspot is of the same order as the horizontal dimensions, as illustrated in Figure 3, from [Pa79]. The third theoretical model is called the cluster model.

The monolithic models of sunspots are developed on a well-defined set of mathematical equations, but have difficulties in explaining why the surface temperature of ∼3 900 K and the magnetic field strength of 3 kG seem to be independent of sunspot dimensions. The cluster model introduced by E. N. Parker in 1979 [Pa79] is, on the

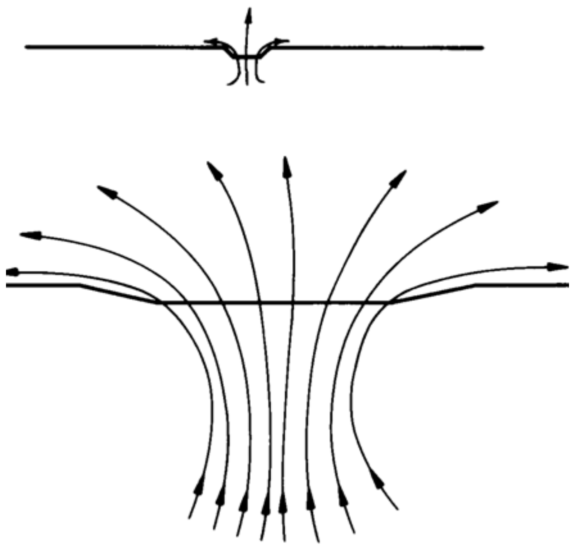

Figure 3: *Cross-section sketch illustrating the scaling of the magnetic structure of sunspots according to monolithic sunspot models by E. N. Parker [Pa79].*

other hand, not firmly developed on a mathematical basis, but explains the mentioned qualitative features well.

In the cluster model, a sunspot is made up of a bunch of flux tubes held together by buoyancy forces due to the fanning out of field lines in the upper photosphere, appearing as one single visible unit. A qualitative sketch by E. N. Parker is presented in Figure 4. Any small flux tube that tries to separate from the unified cluster in the upper photosphere, has to move outward and downward against the stabilizing buoyancy forces. Further down, where the sides of the flux tubes decline to the vertical direction, the buoyancy forces can no longer stabilize the cluster, and the flux tubes break apart. The depth where this happens can be thought as approximately the same for all sizes of sunspots. There might also be a characteristic size of the separate flux tubes involved, which might explain the independence of sunspot size to parameters such as surface temperature and magnetic field strength.

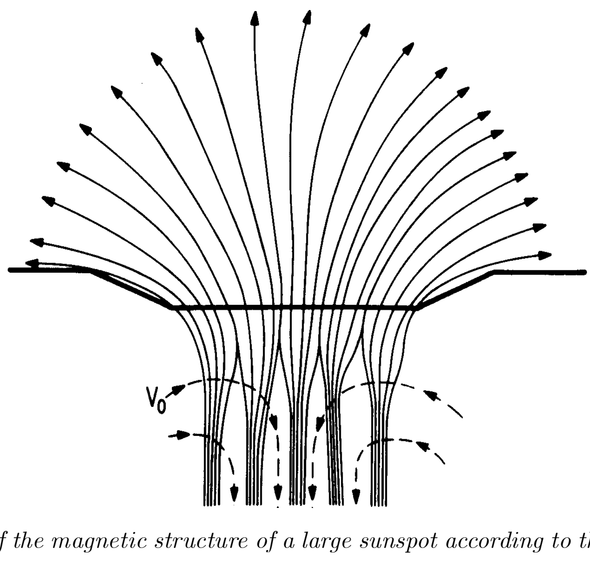

Figure 4: *Cross-section of the magnetic structure of a large sunspot according to the cluster model [Pa79].*

2.5 Limb Darkening

The brightness of the solar disc falls off near the limb. This phenomenon is called limb darkening. The temperature of the different regions of the Sun decreases with distance from its centre. When looking at the centre of the disc, the observer is looking through photospheric layers until the photosphere becomes opaque. The light seen comes mostly from the hotter and therefore more luminous lower-lying regions of the photosphere. On the other hand, when looking towards the limb the line of sight is in the direction of the upper, cooler and less bright levels of the photosphere. [Ni82]

2.6 The Wilson Effect

The sunspots look different during their passage from the eastern to the western limb. When the spot is located at the eastern limb, the west side of its penumbra is thinner than the east side and vice versa. This implies that the sunspot is a saucer-shaped depression into the surrounding photosphere and is called the Wilson effect after its discoverer A. Wilson, a Scottish astronomer, in 1769 [Ni82]. The effect is caused by the sunspots being less dense and therefore having a lower opacity than their surroundings, which means that the observed light comes from a greater depth. [Ni82] [Pr84]

3 DPD - Debrecen Photoheliographic Data

The Debrecen Photoheliographic Data (DPD) is the most detailed sunspot data set available ([Ba01]).

3.1 Overview and History

Why not start from the very beginning? Solar physics in Hungary began with two great personalities, Miklós Konkoly Thege (1842-1916) and Gyula Fényi (1845-1927).

Konkoly had very many interests, both scientific and others, and astronomy was only one of them. He conducted full-disc graphical observations covering every day from 1873 to 1916 at his self-founded Observatory in Ógyalla, Hungary, today Hurbanovo, situated in Slovakia. He also has the credit of having founded the first Hungarian Observatory, today named Konkoly Observatory belonging to the Hungarian Academy of Sciences, of which the Debrecen Heliophysical Observatory is the solar department.

Fényi's greatest interest was prominences. He went through the solar limb with his prominence spectroscope and gathered a huge amount of drawings between the years of 1885 and 1920. His residence was the Haynald Observatory at Kalocsa of which he was the director. Fényi had about 185 publications, still today considered a great number.

Details from a photospheric drawing made at Kalocsa observatory on October 20, 1905 can be found on the cover of this diploma work.

The observations of these two eminent men have been enlarged with about 200 000 photographic plates since 1958 by the Debrecen Heliophysical Observatory.

The Debrecen Photoheliographic Data is a catalogue containing sunspot parameters. The production of the DPD is based on analyses of full-disc solar photographic plates in the continuous visible spectrum of light, or white-light for short. Parameters included in the data set are those extractable from full-disc solar photographic plates, as position and area of the umbra and penumbra, not only for sunspot groups but also for individual spots. It is the only sunspot catalogue taking into account every spot observed, even the smallest ones.

The ancestor of this data set is the Greenwich Photoheliographic Results, being the classical catalogue containing sunspot characteristics for every day from the year 1874 to 1976. Beginning with 1977, the programme was taken over by the Debrecen Heliophysical Observatory, and the Debrecen Photoheliographic Results (DPR) was born. Being a more complex catalogue than the one it is the continuation of, the process of compiling data is slow. This delay has given rise to a new catalogue, the DPD. Preparations for the production of the DPD began in 1992 and the first compiled year of the series was introduced in 1996.

Like the DPR and the Greenwich catalogue, the DPD contains data for every day of the year. Observations are made at the Debrecen Heliophysical Observatory and its Gyula observing station, situated 150 km from Debrecen.

3.2 Observational Technique

The sections to come describe the instruments and the observational material at the Debrecen Heliophysical Observatory, along with an explanation of how systematic errors are avoided.

3.2.1 Instruments and Observational Material

The photoheliographs used in Debrecen and Gyula are quite similar. Both are from the end of the 19th century, the one in Debrecen was constructed in 1882. Quality and accuracy are not all about modern equipment though, but good optics and making the most out of the instrument. The aperture is about 14 cm with a focal length of nearly two metres. Both heliographs house a magnifying lens system, projecting an about five times enlarged image on the secondary focal plane. The photos are taken through a yellow filter on 13×14 cm negatives. The diameter of the solar disc is 11 cm on the Debrecen plates and 10 cm on the plates taken in Gyula. The crosshairs, made of spider-wire, at the focal plane of the objective are oriented in the north-south and east-west directions respectively.

3.2.2 Systematic Error Reduction

If the weather conditions are favourable, observations are made several times a day and the best set of plates is chosen for analyses. Each observation consists of three plates taken in order to reduce systematic errors, as described below.

The plane of the photographic plate should be perpendicular to the secondary focus in order to ensure a completely sharp image. The inclination of the photographic plate, if present, can be deduced by taking one picture from the east and one from the west side of the pier on which the heliograph is mounted.

In order to determine the deviation angle of the north-south directed spider-wire from the real north-south direction, a double exposure of the solar disc is made with the clockwork stopped and with an interval of about two minutes. This procedure results in a plate with two, overlapping solar discs, as illustrated in Figure 5. The line joining the two intersection points of the limbs of the solar images is the correct north-south direction. The angle between this intersection line and the north-southerly directed spider-wire enable a very accurate position determination of sunspots.

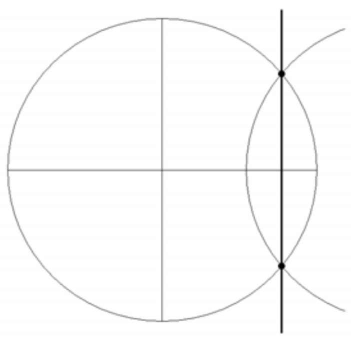

Figure 5: *A schematic illustration of the double exposure of the solar image.*

3.2.3 Procedure for Cloudy Days

About 300 days a year can be covered by daily observations made at either the Debrecen or the Gyula observing station. When weather conditions prohibit photoheliograms to be made at either of these two sites, plates from other observatories around the world have to be provided. Finding material for missing days is a challenging task since it is not certain that a full-disc, white-light image was taken anywhere a specific day.

The list of all observatories contributing with photoheliograms to the production of the DPD can be found in Appendix A where also the number of plates from the different observatories included in the DPD are indicated.

3.3 Measuring Positions and Areas

Two very important parts of the production process of the DPD is the measuring of positions and areas of sunspots and sunspot groups.

3.3.1 Position

The position measurements of the sunspots are done by first determining the positions of the four points at the intersection between the spider-wires and the solar limb. In addition, 12 more points are measured around the limb, three between each intersection point. This procedure enables the position determination of sunspots with respect to the solar limb or the centre of the crosshairs. The accuracy of the position determination is about 1/10 of a heliographic degree.

When the real north-south direction of the solar disc on the photoheliogram is known, derived as described in Section 3.2.2, the Sun's rotational axis on the disc can be calculated.

As motivated in Section 3.2.2, one observation consists of three plates of which all are measured in order to minimize positional errors, but only the best quality plate is digitized for the area measurement to be carried out.

3.3.2 Umbra and Penumbra Areas

The digitization of the plates is done with a 16-bit camera. The whole plate cannot be digitized at the same time, because the resolution would not be high enough. Each sunspot group is taken separately. The sunspots on each piece of the solar disc are put under the 16-bit camera and the position measurements of the same spots on the original photoheliogram are fitted to each other.

The border between the umbra and penumbra and between the penumbra and the photosphere is indicated by differences in intensity on the digitized image. In the ideal case the edges are obvious jumps in intensity, but nothing is ever easy. A software developed by L. Győri recognizes the rim of the umbra and the penumbra, but it is easy to modify by hand, which is done in many cases. Every border is checked by an observer before it is approved. The areas are rounded to integers in the definite version of the catalogue.

In case of small spots, it can from time to time be difficult to decide whether it is a spot or a pore. In these situations all three plates are examined, but it should be stressed that the spot does not have to be visible on all plates to be considered a spot.

Measurements of sunspots close to the limb can contain uncertainties due to the limb darkening (see Section 2.5) and the fact that the contrast between the photosphere and the spots is lower than closer to the centre of the solar disc. It can sometimes be difficult to see the difference between spots and the granulation.

3.3.3 Resolution

A resolution of one arcsecond or better can be achieved for the photoheliograms when the weather conditions are good, but is not as good during for example wintertime, when the Sun stands lower. Gyula observing station has often better quality plates than Debrecen because it is situated at an altitude of 40 m on top of a water tower, whereas the Debrecen telescope is situated 10 m above ground level. The resolution is limited because of atmospheric motions, but the height difference between the two sites makes the air turbulence lower for Gyula observing station.

3.4 Catalogue Extension

To date, the DPD consists of three published and five unpublished years. The published years are 1986 to 1988 ([Gy96], [Gy98], [Gy01]), and the set of unpublished years contain the almost complete year of 1989 (January to November) together with 1993 to 1996. The latter years are not published because they still have some gaps. In the case of 1996 only one December-day is missing, but photographic plates from other observatories are, as described in Section 3.2.3, not easy to obtain.

The most recent data are August to November 1989, finished in mid November 2002. This means that we have only had the first part of the year to our disposal during our analyses.

The area data for the year 1986 and the first half of 1987 were measured with the oldest method, a machine called Dareal. With the second half of 1987, the method was changed and the sunspot groups were digitized with an 8-bit camera, which also was used for digitizing all observations for the first two months of 1993 and for all foreign plates that year. The rest of the 1993 analyses were redone with a 16-bit camera. The year 1993 was followed in chronological order by 1988, 1994, 1996, 1995 and 1989, for all of which a 16-bit camera was used.

The published years are, of course, checked. Among the unpublished years the first half of 1993 and all 1996 data are checked.

3.5 Catalogue Structure

The DPD catalogue consists of two parts, a numerical and a graphical one. Let us first consider the latter.

3.5.1 The Graphical Catalogue

Each active region that is found on the photographic plates is scanned. These pictures are available in .jpeg and .fits-format in the digital library of the Debrecen Heliophysical Observatory, accessible at their ftp-server. Every measured spot in a sunspot group is numbered, see Figure 6 for an example. The numbers indicated on the pictures are the same as in the numerical catalogue. The header contains information about the name of the observing station, the date and time for the observation and the NOAA[1] sunspot group number. In the figure, the resolution is marked by showing the corresponding dimension of one arcsecond in the direction of the rows and columns of the picture. Also the heliographic north and west directions of the centre of the disc are indicated.

The photographic plates are digitized with a 16-bit camera, as earlier mentioned, but the published images are converted to 8-bits to make them easier to handle. The aim with the graphical catalogue is not for the viewer to be able to redo the measurements found in the numerical catalogue, but to be able to do complex analyses. The pictures

[1]The sunspot group number as given by the National Oceanic and Atmospheric Administration (NOAA).

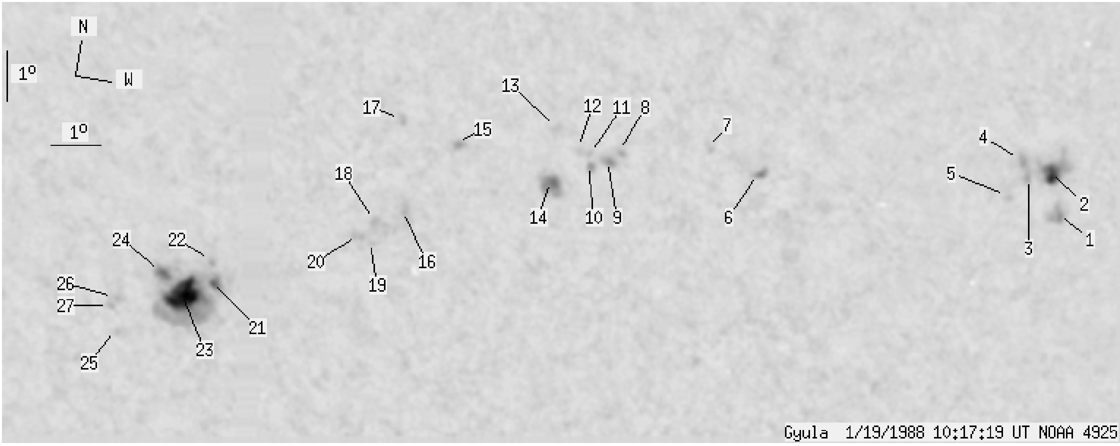

Figure 6: *This is the scanned image of the sunspot group with NOAA number 4925 on January 19, 1998. Each figure in the graphical catalogue, like this one, contains one spot group, and the spots within the sunspot group are numbered. The spot numbers correspond to the numbering in the numerical catalogue.*

enable the analyzer to view the group morphology and to make comparisons with other observations as magnetic and H-alpha.

3.5.2 The Numerical Catalogue

The numerical catalogue consists of a series of text files (ASCII), one for each year, with a certain format. Here follows a shortened explanation of what can be found in these text files. The complete version of the explanation can be found in [Gy96], [Gy98] and [Gy01].

Table 2 contains an extract of the 1996 catalogue, and it clearly demonstrates the three different types of rows that the catalogue contains. The row beginning with a 'd', standing for 'day', contains information about the sunspots visible that specific day, given by the date. It is possible to gain information about the origin of the observation, in this case the Debrecen observatory, the daily sum of the projected umbra area, the measured total, i.e., umbra plus penumbra area, the for foreshortening corrected umbra and total area, and the Julian Date. Also the position angle P of the northern extremity of the axis and the heliographic latitude B_0 of the central point of the disc at the time of observation are indicated. All projected area measurements in all three kinds of rows are given in units of millionths of the solar disc, whereas the corrected areas are given

d1996	130.361	DEBR		8	40	5	25	2450112.861	-11.21	-5.86		
g1996	130.361	7943		2	7	1	4	10.28	192.78	7.90	333.97	0.3097
s1996	130.361	7943	1	2	7	1	4	10.28	192.78	7.90	333.97	0.3097
g1996	130.361	7944		6	33	4	21	10.06	218.93	34.08	294.98	0.6110
s1996	130.361	7944	1	3	15	2	10	10.18	219.34	34.48	294.90	0.6167
s1996	130.361	7944	2	0	7	0	4	10.48	219.09	34.24	295.50	0.6153
s1996	130.361	7944	3	3	10	2	6	9.54	218.41	33.56	294.54	0.6016
s1996	130.361	7944	4	0	1	0	1	10.29	217.33	32.47	296.42	0.5922

Table 2: *This extract from the 1996 numerical catalogue illustrates how the data is stored in the DPD catalogue. There is a 'day'-row for each day of the year followed by rows for the observed groups, if any, the specified day, followed by rows for each spot in the sunspot groups. On January 30, 1996 there were two sunspot groups visible on the solar disc consisting of one and four sunspots, respectively.*

in millionths of the solar hemisphere[2].

If there were no spots visible on the solar disc, the 'day'-row is followed by the next 'day'-row and the areas and positions are zero. On days with active regions visible though, the 'day'-row is followed by a row beginning with the letter 'g', which stands for 'group'. Here information about the group or groups in NOAA sunspot group number order is listed. Like the 'day'-rows, the 'group'-rows contain the date and time for the observation and also the NOAA number, the sum of the umbra and total projected and corrected area of the group, the heliographic latitude (B) and longitude (L), the longitudinal distance (LCM) from the solar central meridian, the position angle and finally the distance from the centre of the solar disc measured in units of the solar radius.

Since each sunspot group is divided into spots, the next line or lines are dedicated to the spots within the group. These rows begin with the character 's' for 'spot'. Again the lines start with the date and time for the observation. Further tabulated parameters for sunspots are the NOAA sunspot group number, i.e., which group the specified spot belongs to, the spot number within the group, the projected and corrected umbra and total spot area, B, L, LCM, the position angle and the distance from the centre of the solar disc for each spot. The position of a spot means the position of the centre of the umbra, if any, otherwise the centre of the penumbra is given.

The case of several spots sharing a common umbra or penumbra, is marked by a negative value in the projected umbra or total area column respectively. The negative number indicates at which spot the total area for the common umbra or penumbra can be found, in the manner shown in Table 3. Spots sharing a common umbra occur when an umbra consists of fragmented regions, which cannot be separated without losing umbra area. It is also worth mentioning that the spots within a group do not bear the same number every day, since it would be an enormous work identifying every spot from one day to the next. The spot numbering is thus arbitrary.

The total area given for each group is the sum of the areas of all the spots in that group, and the daily sum of the areas are based on these numbers. The mean position of each group is calculated by multiplying the positions of all separately measured spots of every group by their corrected total areas and dividing the sums of the products by the sum of the areas.

When a penumbra contains more than one umbra, the position of the centre of gravity of the components is determined by weighting the positions of the umbrae with the corrected umbra areas before the mean position of the whole group is calculated.

Intermittent[3] sunspot groups are indicated with zero areas in the catalogue and no positions are given.

[Gy96] [Gy98] [Gy01]

[2] 1 millionth of the solar hemisphere corresponds to a circular sunspot with a diameter of 1970 km and an area of about $3.0 \cdot 10^6$ km^2.

[3] Coming and going at intervals; not continuous

d1988	829.310	DEBR		507	3513	422	2667		2447402.810	20.43	7.15	
g1988	829.310	5131		170	1420	179	1097	-19.27	256.43	-55.54	116.94	0.8724
s1988	829.310	5131	**1**	0	10	**0**	**8**	-17.63	262.13	-49.85	117.37	0.8224
s1988	829.310	5131	**2**	0	3	**0**	**3**	-20.28	262.80	-49.17	120.63	0.8270
s1988	829.310	5131	**3**	31	420	**27**	**376**	-18.75	261.15	-50.83	118.19	0.8350
s1988	829.310	5131	**4**	0	1	**0**	**1**	-17.11	260.30	-51.68	116.00	0.8364
s1988	829.310	5131	**5**	1	-3	**1**	**-3**	-19.12	260.75	-51.23	118.42	0.8397
s1988	829.310	5131	**6**	2	23	**2**	**21**	-16.66	259.85	-52.13	115.31	0.8387
s1988	829.310	5131	**7**	4	-3	**3**	**-3**	-18.69	260.44	-51.54	117.82	0.8408
s1988	829.310	5131	**8**	16	-3	**14**	**-3**	-19.39	260.48	-51.50	118.60	0.8429
s1988	829.310	5131	**9**	0	1	**0**	**1**	-17.45	259.51	-52.47	116.05	0.8442
s1988	829.310	5131	**10**	3	-3	**3**	**-3**	-20.42	259.50	-52.48	119.31	0.8544
s1988	829.310	5131	**11**	0	1	**0**	**1**	-18.80	258.93	-53.04	117.31	0.8534
s1988	829.310	5131	**12**	15	209	**14**	**199**	-18.46	258.45	-53.52	116.75	0.8562
s1988	829.310	5131	**13**	0	4	**0**	**4**	-19.76	258.61	-53.36	118.23	0.8592
s1988	829.310	5131	**14**	-12	-12	**-12**	**-12**	-18.40	258.06	-53.92	116.52	0.8591
s1988	829.310	5131	**15**	0	8	**0**	**8**	-19.48	258.30	-53.67	117.80	0.8606
s1988	829.310	5131	**16**	0	1	**0**	**1**	-17.50	256.57	-55.41	114.98	0.8682
s1988	829.310	5131	**17**	1	8	**1**	**8**	-19.40	257.18	-54.79	117.27	0.8691
s1988	829.310	5131	**18**	1	6	**1**	**6**	-19.73	256.75	-55.23	117.46	0.8734
s1988	829.310	5131	**19**	0	1	**0**	**1**	-17.57	255.93	-56.05	114.82	0.8733
s1988	829.310	5131	**20**	6	-12	**7**	**-12**	-18.77	256.16	-55.82	116.20	0.8749
s1988	829.310	5131	**21**	6	24	**6**	**25**	-20.50	256.42	-55.55	118.16	0.8781
s1988	829.310	5131	**22**	0	14	**0**	**14**	-19.91	255.69	-56.28	117.26	0.8817
s1988	829.310	5131	**23**	0	4	**0**	**4**	-20.80	255.42	-56.56	118.10	0.8862
s1988	829.310	5131	**24**	0	5	**0**	**5**	-21.07	255.21	-56.77	118.30	0.8884
s1988	829.310	5131	**25**	0	3	**0**	**3**	-20.71	255.07	-56.91	117.87	0.8884
s1988	829.310	5131	**26**	0	6	**0**	**7**	-20.64	254.43	-57.55	117.57	0.8927
s1988	829.310	5131	**27**	1	334	**1**	**-32**	-18.18	253.37	-58.60	114.60	0.8938
s1988	829.310	5131	**28**	2	-32	**2**	**-32**	-19.62	253.31	-58.67	116.10	0.8977
s1988	829.310	5131	**29**	9	-32	**10**	**-32**	-18.42	252.51	-59.47	114.57	0.9004
s1988	829.310	5131	**30**	1	-32	**2**	**-32**	-20.63	252.48	-59.50	116.88	0.9058
s1988	829.310	5131	**31**	14	-32	**16**	**-32**	-18.48	251.50	-60.48	114.30	0.9073
s1988	829.310	5131	**32**	40	334	**48**	**401**	-20.54	251.45	-60.53	116.45	0.9123
s1988	829.310	5131	**33**	17	-32	**21**	**-32**	19.86	250.20	-61.78	115.34	0.9186

Table 3: *The case of several spots sharing a common umbra or penumbra, is marked by a negative value in the projected umbra or total area column, respectively. The negative number indicates at which spot the values for the common umbra or penumbra can be found. In the table the bold columns are, from left to right, sunspot number, umbra area and total area.*

4 Other Sunspot Databases

There are several sunspot databases produced by single or networks of observatories around the world, all with their own flavour. This section gives a short overview of the most known sunspot data sets.

A common feature for the different sunspot databases is that a number is given to each sunspot group in the order of appearance and retained until the group disappears around the western limb or dies out. This number is in the case of the DPD identical with the number given by the National Oceanic and Atmospheric Administration (NOAA).

4.1 Greenwich Photoheliographic Results

The Greenwich series of solar photographs is the classical sunspot database and it commenced in April 1874. More than one hundred years later, in 1977, the catalogue changed and the umbra area data were only estimated, until 1981, which is the last year of the catalogue. This very first database has been very important and has enabled many analyses and publications.

The photographs of the Sun obtained at Greenwich Royal Observatory were taken with a 10.16 cm photoheliograph. In 1910 the original object glass was replaced by a photographic objective. The original enlarging system was improved in 1926, giving an image of the Sun of about 19 cm in diameter.

The measures of the photographs for each day were made with a large position-micrometer. The area counts were carried out with a magnifier with a scale glass accurately ruled with cross-lines into squares with sides of one hundredth of an inch (0.254 mm, corresponds to two millionths of the solar hemisphere). The integral number of squares and parts of squares that covered the spot was estimated by the observer.

The Greenwich Photoheliographic Results contain the following parameters for sunspot groups and until 1915 also for spots: time of observation, group number, distance from the solar centre in terms of the solar radius, the position angle measured from the north pole of the solar axis, heliographic longitude and latitude, umbra and whole area corrected for foreshortening.

At NOAA National Geophysical Data Center (NGDC) the data for sunspot groups in the Greenwich Photoheliographic Results were digitized and are available in electronic form from 1874 to 1981. [Ch05] [De87] [Jo38] [Jo57] [La75] [Ne58]

4.2 DPR - Debrecen Photoheliographic Results

The daily photoheliographic programme of the Royal Greenwich Observatory was after its termination in 1976 taken over by the Debrecen Heliophysical Observatory and the Debrecen Photoheliographic Results (DPR) were born. The DPR indicates among other characteristics, unlike the DPD, the polarity of the considered sunspots and remarks about the evolution and types of the sunspot groups. During the course of compiling both the DPR and the DPD all sunspots recognized as such on the photoheliograms are measured. However, spots published in the DPR are only those that can be identified day by day during their whole lifetime, or spots that are important for the developing process of the sunspot group they belong to.

The detailed analyses of the evolution of the groups and the polarity data of spots provide very useful information for further study, but they demand a tremendous and time-consuming work, and the publication of the DPR suffers an enormous delay. The available years are 1977 and 1978.

4.3 SOON - Solar Optical Observing Network

SOON stands for Solar Optical Observing Network and is operated by the U.S. Air Force since 1976. It is used for space weather specification and forecast. The SOON consists of five solar observatories around the globe at widely spread longitudes in order to allow observations 24 hours a day. The database is graphical, i.e., is based on sunspot drawings made daily on each site from a projected solar image with a diameter of 18 cm. The five observing stations are Palehua on Hawaii, Holloman in the U.S., Ramey in Puerto Rico, San Vito in Italy and Learmonth in Australia, as illustrated by Figure 7.

For the purpose of SOON, real time observations are needed day to day. Therefore, time is of the main interest and accuracy is of lower priority. Sunspots smaller than ten millionths of the solar hemisphere are usually not considered. [Ba01]

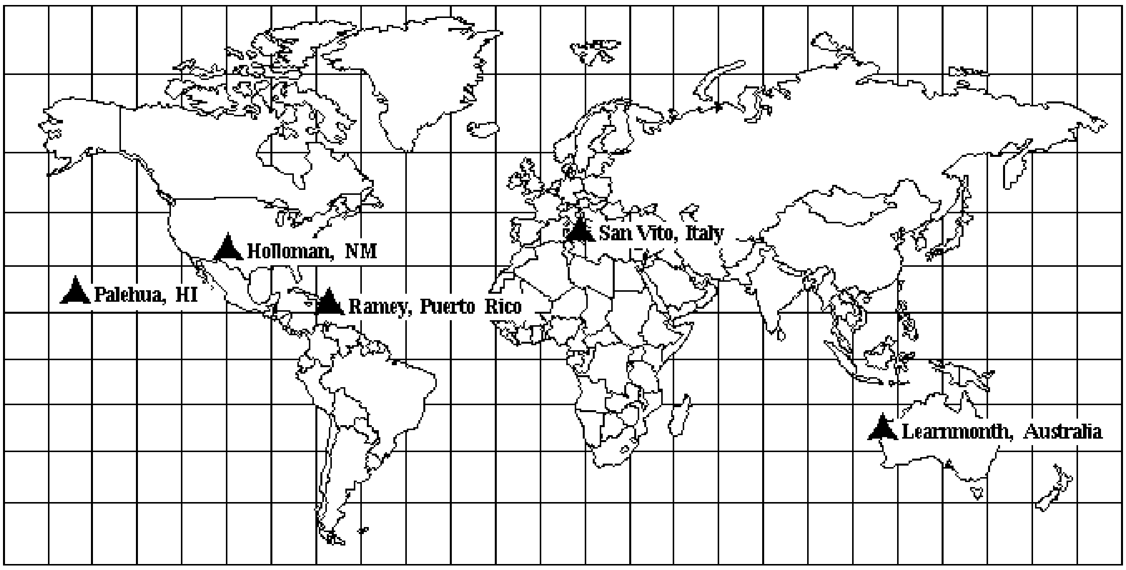

Figure 7: *Map showing the five SOON sites. (Picture from NOAA.)*

4.4 Mount Wilson Data

The series of white-light photographs taken at the Tower Telescope at Mount Wilson, U.S., was begun in 1916. The Tower Telescope is located inside a dome at the top of an 18 m high tower and has an aperture of 30 cm. The solar image photographed has a diameter of 17 cm.

The Mount Wilson data contain parameters for the observed sunspots and sunspot groups as, for example, classification of the sunspot penumbra and the sunspot group compactness. Given are also the maximum magnetic field strength in every group measured, and of course the position for the sunspots and sunspot groups. Also the areas of sunspots are measured, but only the total area is made available. The umbra and penumbra areas are not separately indicated. The data are not corrected for atmospheric refraction, optical aberration or any other effect, which makes it difficult to work with. [Ho84] [Ho99]

4.5 Catania Astrophysical Observatory

The sunspot catalogue published by the Catania Astrophysical Observatory, Italy, is based on daily full-disc white-light photographs taken with an hourly frequency and one drawing per day of pores, sunspots and faculae[4]. The drawings are made from a projected solar image with a diameter of 24.5 cm.

Some of the parameters listed in the Catanian catalogue are position, type and area of each sunspot group and also the total number of spots and pores in each group. [Te95]

4.6 Solar Phenomena

The Solar Phenomena bulletins are published by the Rome Astronomical Observatory. They contain information about position, class, number of spots, total and umbra area for sunspot groups.

4.7 The Chinese Solar-Geophysical Data

The Chinese Solar-Geophysical Data are produced by the Chinese Academy of Sciences and contains position, daily total area of sunspot groups and also magnetic and velocity fields of solar active regions.

4.8 Sunspot Index Data Centre

The main task of the Sunspot Index Data Center at the Royal Observatory of Belgium is to gather the observational data of several observatories and to compute and broadcast the daily, monthly and yearly international sunspot numbers, defined by Equation (1) in Section 2.2.

4.9 Conclusions

There exist several other solar data sets than the DPD, but investigations fully comparable to those described in the sections to come cannot be done on any of them. The other catalogues are either not as precise and detailed as the DPD in the matter of small sunspots, they do not provide the sunspot parameters we need, or they do not cover a time period long enough for the conclusion of a quasi-biennial periodicity being present.

[4] In white-light, photospheric faculae are brightenings that mark active regions. Faculae have greater temperatures and densities than their surrounding. [Ze98]

5 Earlier Investigations on the Umbra-Penumbra Ratio

Investigating sunspot parameters is not a new activity. This section discusses briefly some of the analyses made during the years.

5.1 On the Umbra-Penumbra Area Ratio

P. N. Brandt, W. Schmidt and M. Steinegger [Br90] have investigated the umbra-penumbra area ratio for 126 sunspots and sunspot groups. The analyses are based on sunspot photographs taken by the 40 cm Vacuum Newton Telescope at the Teide Observatory, Tenerife, from August 9 to September 1980, near the maximum of the solar cycle number 21. The results show a linear relation between the logarithm of the umbra and the penumbra area. The average umbra-penumbra area ratio found was 0.24 for small spots and 0.32 for large spots. Sunspots with a total area of around 50 millionths of the solar hemisphere are referred to as small.

When we dug deep to find earlier results on the umbra-penumbra area ratio investigations, we found several articles claiming that the umbra-penumbra area ratio for sunspot groups generally tends to follow the solar cycle. One example is an inquiry made by L. Dezső and O. Gerlei [De64]. They have plotted the two-year means for sunspot groups with an umbra area larger than or equal to 10 and smaller than 40 millionths of the solar hemisphere in the Greenwich catalogue, observed between 1886 and 1955. Other examples are the article by A. Antalová [An71] and references therein.

5.2 Conclusions

The conclusions drawn from earlier investigations on the umbra-penumbra area ratio is that spots with an umbra area smaller than 10 millionths of the solar hemisphere have not been investigated.

Investigating 126 sunspots and sunspot groups, as done by P. N. Brandt, W. Schmidt and M. Steinegger, is a small statistical sample. To be able to draw quantitative conclusions about the real umbra-penumbra area ratio a larger set of data has to be considered, and spots and sunspot groups have to be taken into account separately. Sunspots and sunspot groups should not be mixed because they are distinct phenomena in the sense that groups can contain spots with different characteristics.

The research done by L. Dezső and O. Gerlei and also others, was searching for periods in the penumbra-umbra area ratio comparable with the solar cycle. Such periods can only be traceable as trends in the DPD, since the available catalogue consists of only seven and a half years in total, separated into two intervals, in the ascending and descending phase of the solar cycle number 22.

6 Our Investigations

In this section we describe our expectations and plans for our work. It is always difficult to know in advance how things will work out, and intentions change as features are found that need further investigation, even if this means that other interesting characteristics are left for the future to be discovered.

6.1 Scientific Goal

The goal with our data analyses of the DPD catalogue is to test all kinds of parameters and see if a plot versus time reveals any periodicity whatsoever. The DPD catalogue is unique in its kind as it takes into account even the smallest spots, but has until now been unexplored. We are very agog to find out whether some of the parameters show any solar cycle dependence, as suggested in, e.g., [De64].

A general belief among observers is that the sunspot group compactness varies with the solar cycle and that the greatest spots usually occur before or after the solar cycle maximum [Zi88]. Sunspot group compactness (C_g) is given by

$$C_g = \frac{\sum r_i \cdot a_i}{\sum a_i}, \tag{7}$$

which depends on the distances from the centre of area of the group to the centre of area of the spots (r_i) and the areas of the spots (a_i). Except for investigating this, it would be very interesting to find out whether some heliographic longitudinal bands are more active than others.

Some of the other interesting parameters that we avidly want to investigate are the number of spots per group versus time, the size of spots versus time and the longitudinal distribution of spots within a group.

We have the published years of 1986 to 1988 ([Gy96], [Gy98], [Gy01]) to our disposal but also the unpublished first half of 1989 together with 1993 to 1996. This may sound like too few years, but that depends on what kinds of periodicities the material may contain. It is perhaps difficult to detect an 11-year period, if any, but since maximum occurred in 1989, i.e., in the gap, a trend could be visible since the first years are in the ascending and the later in the descending phase of the solar cycle number 22.

6.2 Attempts Carried into Effect

As a first attempt, we want to delve into the mysteries of the average umbra and penumbra sizes both for groups and spots. We are also very eager to calculate the umbra-penumbra area ratio for sunspot groups. This would help us get acquainted with how calculations easiest are made.

In our calculations of the mean umbra-penumbra area ratio we exclude the spots with zero umbra and/or penumbra area. The DPD contains total and umbra area measurements. We have calculated the penumbra areas from these two parameters.

6.3 Investigation Methods

The first headache to find a cure for is to get the DPD database into a manageable format that is easy to work with. Since the database contains three different rows of information, as described in Chapter 3.5.2, we import the catalogue into three different databases, one for the days, one for the sunspot groups and one for the sunspots. Our task consists, besides the brainwork, mainly of two parts, namely to calculate new parameters out of the given ones, and then to investigate the characteristics of these new parameters by, e.g., making evaluable plots. For the computations on the databases we use Microsoft Access, and when more complicated calculations are needed, we switch to Matlab since we have a better knowledge of that programming language than of SQL and VisualBasic. For making our plots we mostly use the statistical software package SPSS but also Matlab.

We have found SPSS not being the most suitable statistical software for intermittent data sets since it is not possible to automatically make the x-axis represent a continuous time line with gaps in the plot where data are missing. SPSS interprets the x-axis parameter values as categories, one plotted after the other in a user-specified order, but not with internal distances corresponding to the differences of consecutive values producing a continuous time line. This makes error bar plots difficult to interpret if there are no values for some time epochs. In these cases we have been forced to manually put in 'holes' in the time series. Yet SPSS is a very useful software with many easy-to-use functions as its case selecting toolbox.

We calculate half year, quarterly and monthly means of the interesting parameters. Our observational data are continuous in the sense that observations are made every day. However, since sunspots are not every-day phenomena, the occurrence of sunspots on the from the Earth visible hemisphere of the Sun is very discontinuous. In addition to this, sunspots appear with various characteristics in the sense that some of them are lonely and isolated from other spots, while others are gathered in complex groups, as summarized in Table 1 in Section 2.3. As a first attempt we therefore treat all spots alike, averaging their features over time periods of differing lengths.

6.4 Error Reduction in the DPD Catalogue

Due to the human factor it is inevitable that mistakes occur in a partly manual procedure. It is therefore not surprising that during the course of our investigations we have come across some ambiguities, since we are working with partly unpublished material that has not previously been used in analysis. These errors have been reported for correction.

A missing or a duplicate number in the numbering of spots within groups, mismatch between NOAA numbers in the group and spot rows, spots sharing umbra or penumbra with another spot but with a reference in the numerical catalogue to the wrong spot are examples of what we have been able to bring into light. After encountering an inaccuracy we have designed Matlab programmes searching for more of the same type. This has revealed only a handful errors among the 8 376 877 characters of the 107 770 lines on the 1 891 pages of data we have used, which leads us to the conclusion that the DPD is consistent.

7 The Umbra and Penumbra Areas for Sunspot Groups

As our first calculation, we plot the mean sunspot group umbra and penumbra area. In Figure 8 the quarterly mean value of the umbra area with one standard deviation can be seen. This plot tells us that the standard deviation in many cases will probably not be the most suitable dispersion parameter to describe our data graphically since the structure of the data is suppressed by the large standard deviation. The scatter of several of our proposed parameters to study is large due to the wide variety of sunspots, as described in Section 2.3, which will give rise to large standard deviations.

In the rest of this report we will use the estimated standard error of mean, $S_{\bar{x}}$, defined by

$$S_{\bar{x}} = \frac{S}{\sqrt{N}}, \tag{8}$$

where S is the sample standard deviation of the epoch, and N is the sample size. With our data, this parameter is preferable as the choice of the measure of dispersion. We expect trends to reveal themselves as significant variations in the mean values of the investigated parameters. The standard error will be small if the number of observations contributing to a certain mean value is large compared to the standard deviation of the averaged population. However, if the population consists only of a few observations the mean value of the period should be considered less reliable. This is due to the possibility that an occurrence of only a single spot with unusual characteristics can have dominant influence. These epochs will be recognized by their large standard errors.

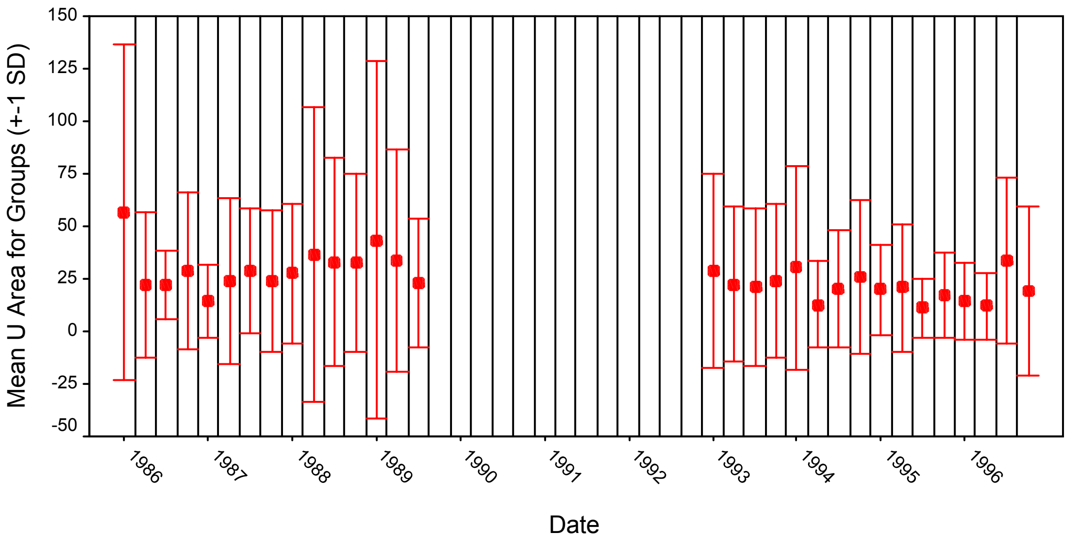

Figure 8: *Quarterly mean of umbra area for sunspot groups with one standard deviation. Each sunspot group is only counted once, namely when its umbra area is the largest.*

7.1 The Mean Umbra Area

The mean umbra area for groups can be viewed in Figure 9. The mean umbra area seems very much to be solar cycle dependent since an ascending and a descending trend with the solar cycle are visible. If we connect the two sides of the plot in Figure 9 we end up with an umbra area peak sometime in late 1990 or early 1991. No conclusions can be drawn, however, because of the lack of data in the middle of our time series.

Some of the monthly mean values, for example February 1986 and the last months of 1996, deviate from the rest of the values. This is because these months contain one or more large sunspot groups that stayed large several days. An example from November 1996 can be found in Figure 11, the sunspot group with NOAA number 7999 as photographed on two different days. The largest spot of the group covered more than 108 millionths of the solar hemisphere five days in a row, while the biggest spots in the other observable groups were at most 69 millionths of the solar hemisphere during the same month.

We are also interested in the umbra area for sunspot groups counting each group only once. The reason for this is to reduce the influence of the long-lived groups. We have chosen to consider every group when its umbra area takes on the largest value of its lifetime. The result is presented in Figure 10. The ascending and descending trend is still visible, but the spread has grown, which can be explained by the reduction of data. The number of months when the average of the umbra area deviates from the big crowd has also grown. The reason for this can be that both the large and small groups are counted when they are the largest and therefore able to raise the mean value above the trend.

7.2 The Mean Penumbra Area

The mean penumbra area for groups show a similar behaviour as the mean umbra area, and is presented in Figure 12. Just like the mean umbra area for groups, the penumbra area seems to peak somewhere late 1990 or early 1991.

The penumbra area values are higher than the umbra area values, which comes from the fact that the penumbra is time to time very difficult to separate into smaller units. A single, large penumbra often contains more than one umbra. This means that several umbrae with a common penumbra can give rise to a large penumbra.

The next plot, Figure 13, shows the mean penumbra area for groups when each group is considered only once, namely when its umbra area takes on the largest value of its lifetime. This figure resembles the group penumbra area plot where every sunspot group is considered as many times as it was observed (Figure 12). The main difference between the two figures is the much greater spread in the latter (Figure 13), which can be explained by the reduction of data.

7.3 Conclusions

Both the mean umbra and penumbra area for groups seem to follow the solar cycle.

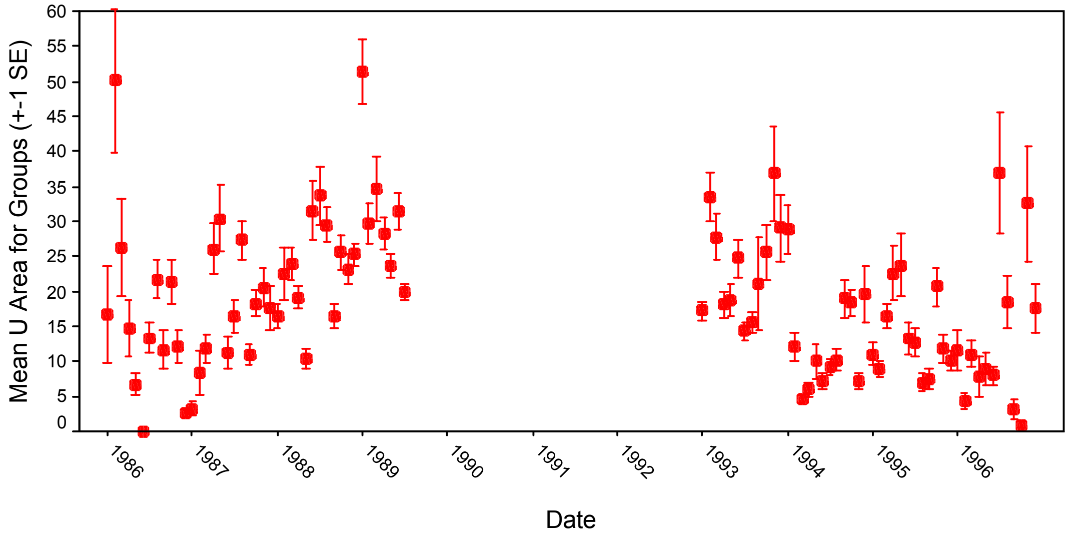

Figure 9: *Monthly mean of umbra area for sunspot groups. Every group is counted as many times as the number of days it lived.*

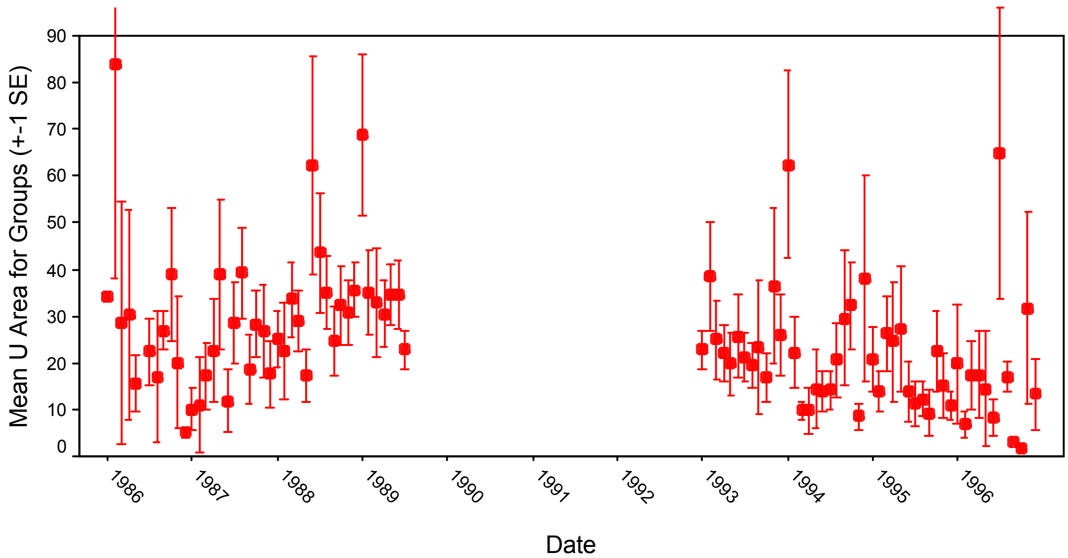

Figure 10: *Monthly mean of umbra area for sunspot groups. Each sunspot group is only counted once, namely when its umbra area is the largest.*

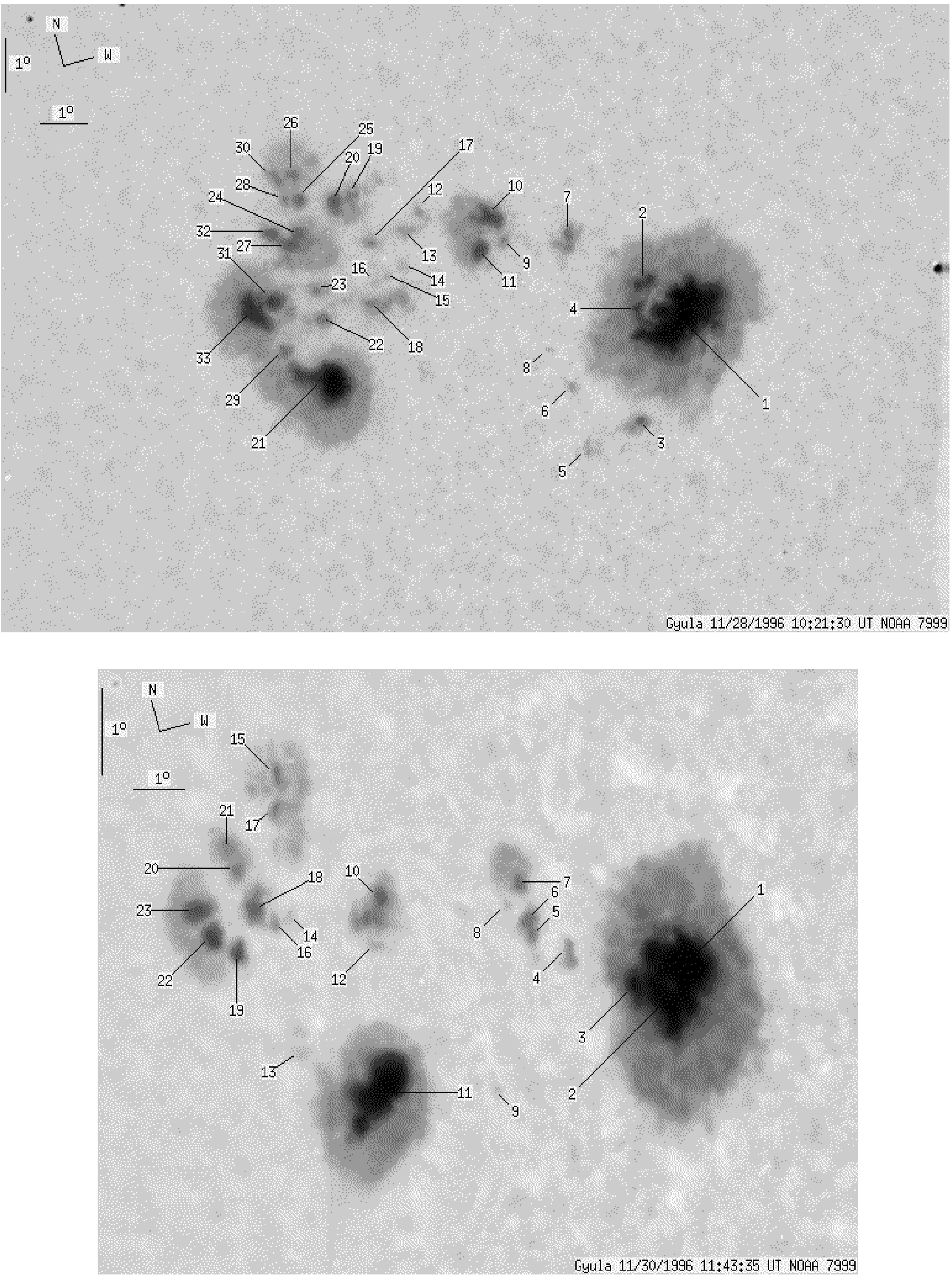

Figure 11: *The sunspot group NOAA 7999 as observed on November 28 and 30. 1996. It stayed very large for five days in a row.*

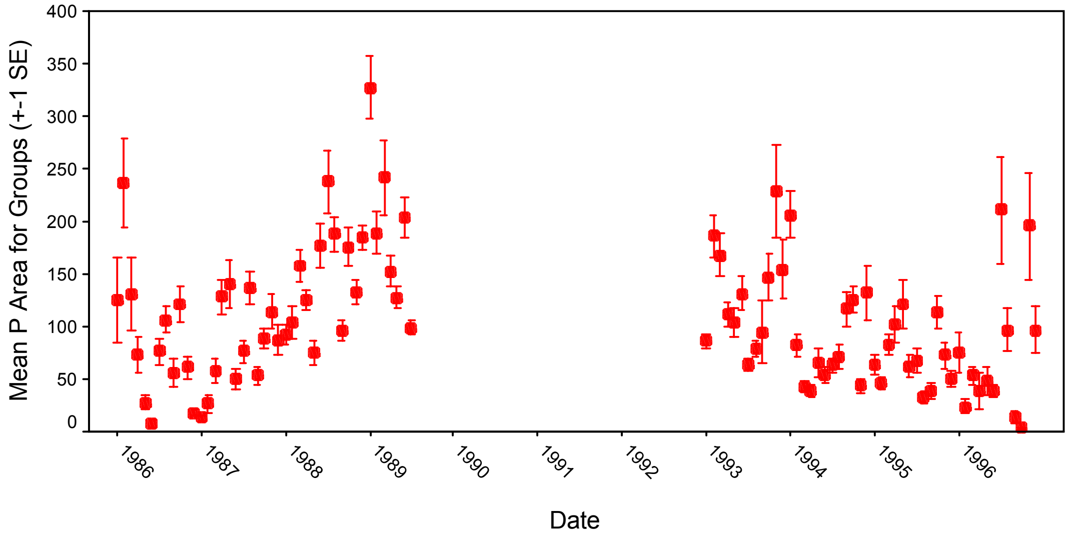

Figure 12: *Monthly mean of penumbra area for sunspot groups. Each group is counted as many times as the number of days it lived.*

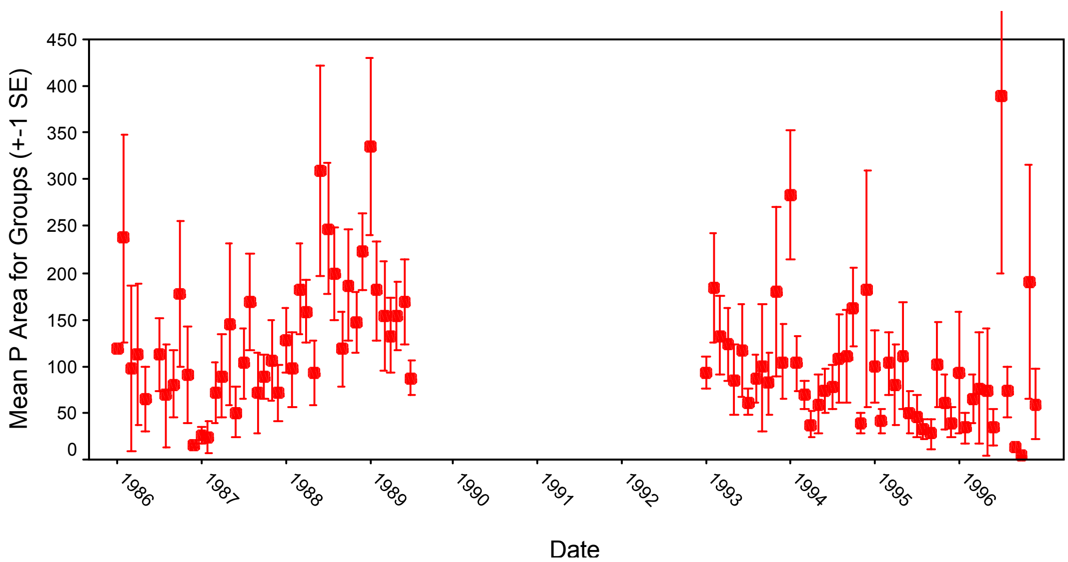

Figure 13: *Monthly mean of penumbra area for sunspot groups. Each sunspot group is counted only once, namely when its umbra area has its maximum.*

8 The Umbra-Penumbra Area Ratio

The umbra-penumbra area ratio is a parameter that can be an important indicator of the magnetic structure of the sunspot umbra and penumbra.

8.1 The Umbra-Penumbra Area Ratio for Sunspots

We start with calculations of the umbra-penumbra area ratio for sunspots and will then also see if the same trend is visible for the umbra-penumbra area ratio for sunspot groups.

8.1.1 Procedure

The first thing to do, before plotting the umbra-penumbra area ratio for sunspots, is to add all the corrected umbra area values to the associated spots. These are indicated by negative numbers in the corrected total area column. The negative number indicates at which spot the values for the common umbra can be found (Section 3.5.2). Another possibility is to omit spots with common umbra or penumbra areas.

The following two statements are valid for the DPD series: A spot cannot share its umbra with other spots without also sharing its penumbra with other spots. On the other hand, a spot can have a common penumbra with other spots but still have an umbra of its own. The summing of umbra area values is a good approximation if the spots are of the same polarity. If they are not, we sum anyway in lack of better procedure since it is out of the scope of this diploma work to study the magnetogram of every spot with shared penumbra area.

The summing of umbra areas is somewhat tricky, since the spots can have common umbrae with spots with lower sunspot number but also higher (see Table 3 in Section 3.5.2). We need a programme that can search in the right direction for the sunspot indicated with a negative number. Matlab is the suitable tool for this task.

8.1.2 All Sunspots Included

The mean umbra-penumbra area ratio with all spots included is presented in Figure 14. Spots with zero umbra or penumbra area, as already mentioned in Section 6.2, are omitted and the between spots shared umbra areas are added. A clear period of about two years can be seen. The amplitude seems to be about 50% of the mean value, but it can be variable.

The data for 1986 are a bit rude in the sense that they do not take part in the trend the rest of the data have agreed on. The period is nevertheless there, and if we imagine a two-year period during the empty years, we can connect the two ends of the graph. The deviating value in late 1996 contains only three small spots, which means that its location off the curve is uncertain. The error bars are evidence of this. The swerving value in mid-95 though, is calculated on 69 spots but since it occurs during a maximum, its deviation is not significant.

There is one monthly mean missing, May 1986. No sunspots were visible during this month.

8.1.3 Each Sunspot Group Only Counted Once

Figure 15 illustrates the mean umbra-penumbra area ratio for spots that lived when the group they belonged to took on the largest value of its lifetime. By making this selection, long-lived and short-lived groups give equal contribution to the summation statistics as every group is counted only once. The error bars have grown, mostly because of the reduction of data, but the two-year period can still be discerned. We can draw the conclusion that the periodic feature of the mean umbra-penumbra area ratio is not caused only by long-lived groups.

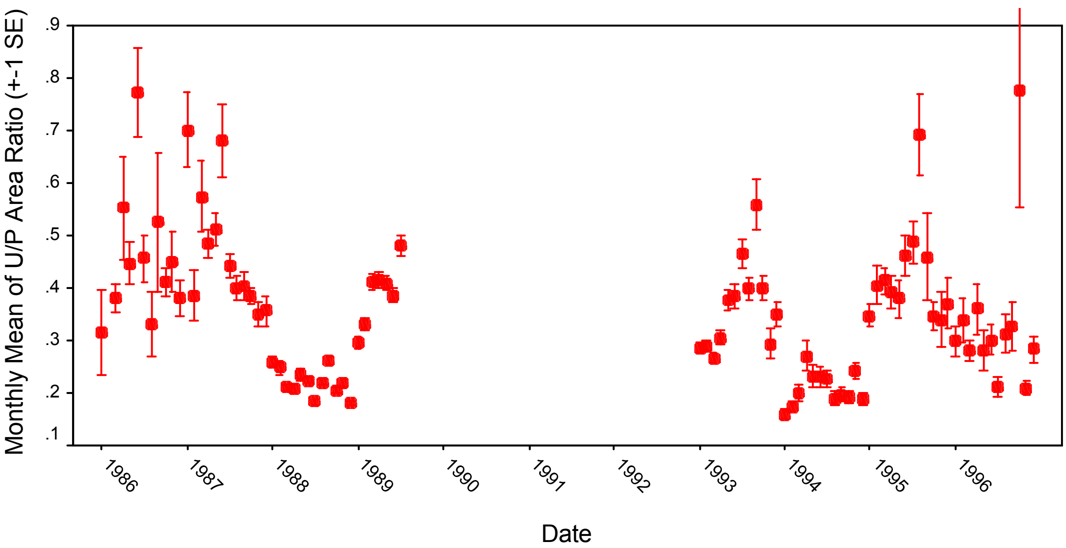

Figure 14: *Monthly mean of the umbra-penumbra area ratio for sunspots with both a distinguishable umbra and penumbra area.*

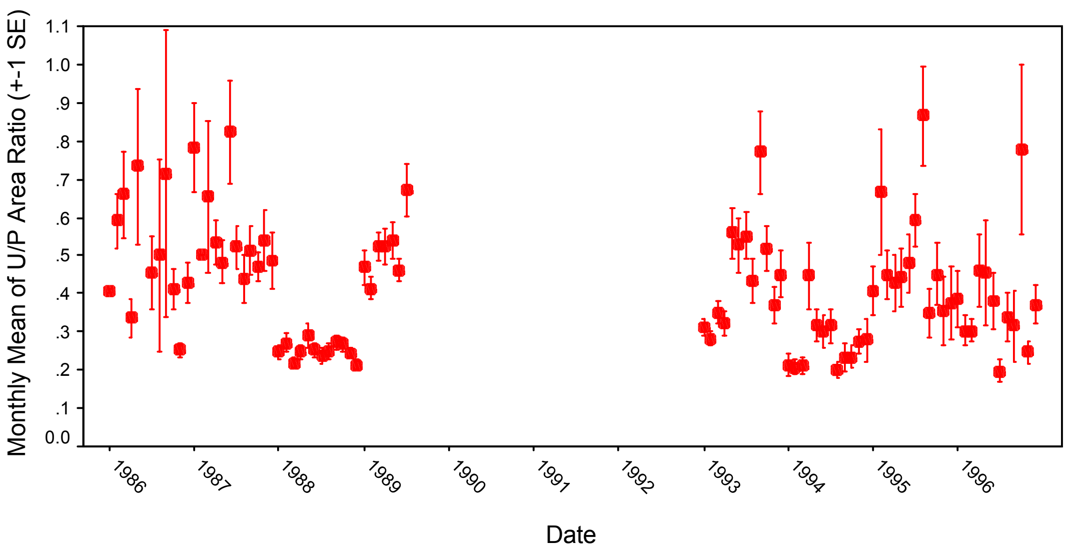

Figure 15: *Monthly mean of the umbra-penumbra area ratio for spots that lived when the group they belonged to was the largest of its lifetime.*

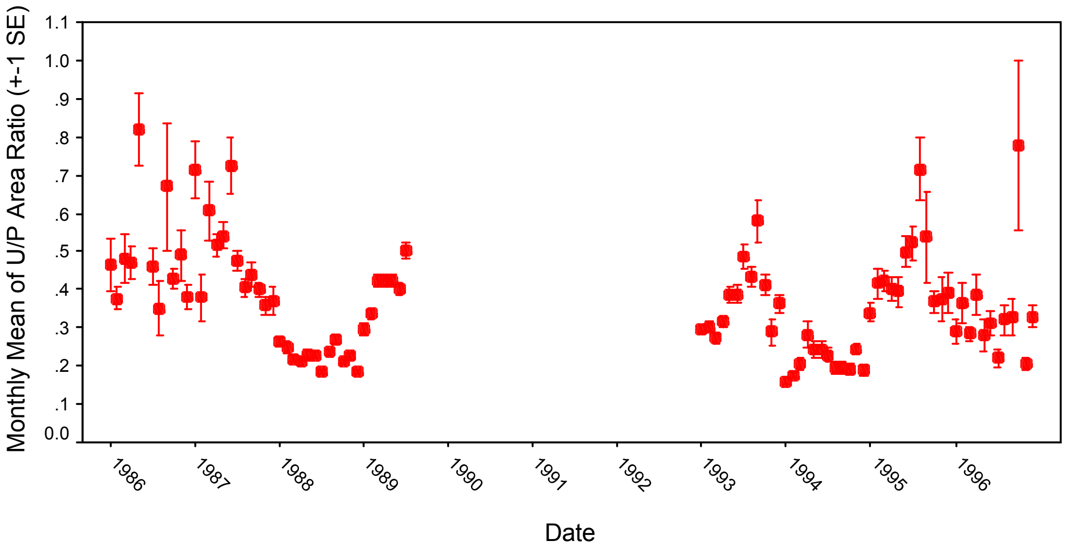

Figure 16: *Monthly mean of the umbra-penumbra area ratio for spots located less than 0.9 solar radii from the solar disc centre.*

8.1.4 Sunspots at the Solar Limb Omitted

One of the possible explanations of the spread of the 1986 data can be the uncertainties in the area measuring process of spots close to the solar limb, as described in Section 3.3. In order to exclude this possibility we have filtered the data for spots with larger distance from the solar disc centre than 0.9 solar radii, which corresponds to an angle of 64° to the LCM, and plotted the remaining spots in Figure 16. The spread of the 1986 values is just as high as earlier.

Another possible cause of the spread can be a low number of sunspots. The number of sunspots during the years we are working with are summarized in Table 4. During the year 1986 the number of sunspots is much lower than during years closer to the cycle maximum. Fewer observed sunspots can very well be the cause the big spread. Also 1996 suffers from a reduced amount of spots, causing larger error bars than previous years (compare with Figure 14).

Year	No of Spots	No of Spots* with U, P, U+P > 0
1986	3060	602
1987	8592	1583
1988	26740	4865
1989**	24580	5171
1993	15181	3384
1994	7923	1170
1995	5910	1100
1996	2179	511
$\sum$	94165	18386

*After having added the umbra values for spots with common penumbrae.

**The year 1989 is not complete. We have data for January to July only.

Table 4: *Number of spots observed during the years in the DPD.*

8.1.5 Sunspots on the Northern and Southern Hemisphere Separated

The next attempt is to separate spots on the northern and southern hemisphere and see if they show the same behaviour. The plot can be seen in Figure 17. A mean umbra-penumbra area ratio value of 1.7 in mid 1986 has been omitted from the plot by zooming in the variable axes. We found this value insignificant because it has a very large standard error of mean and is only based on two sunspots.

The spots on both hemispheres lie on the same curve. The deviating values always belong to either hemisphere, both do not deviate at the same time, and most of the deviating points contain only a few sunspots.

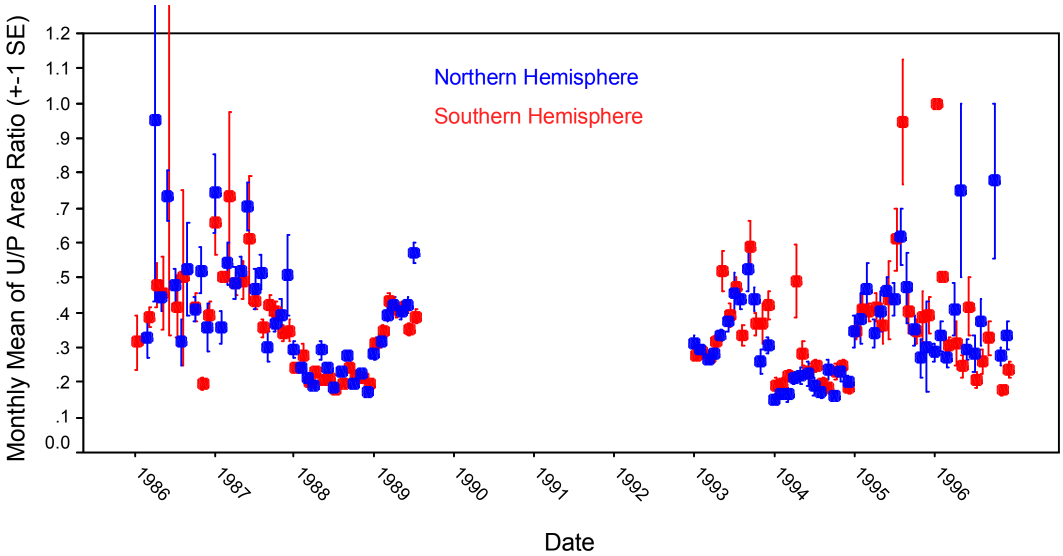

Figure 17: *Monthly mean of the umbra-penumbra area ratio for spots divided into the solar northern and southern hemispheres according to their occurrence.*

8.1.6 Sunspots Divided into Sizes

An interesting aspect is whether all sizes of spots show the same behaviour. For this reason, we have divided the spots into four different size-groups according to Table 5. The graphs for the different spot sizes are presented in Figures 18 - 21. It appears that it is the smallest spots, with a corrected total area less than 15 millionths of the solar hemisphere, that show the most evident cycle dependence (Figure 18). The two-year period is also visible for spots with sizes between 15 and 49 millionths of the solar hemisphere but with lower amplitude, which sinks even more for spots of sizes between 50 and 299 millionths of the solar hemisphere. A comparing graph between the three first size-groups is given in Figure 22, where the decrease of the amplitude with the increase of spot size is evident.

Figure 21 shows that spots with an area larger than 300 millionths of the solar hemisphere do not show any periodicity at all. This can have several reasons. One is the fact that there is a total amount of only 1042 spots this large (see Table 5), which gives less than 12 spots a month on average. Another reason can be that whatever mechanism is causing the quasi-biennial periodicity is less efficient the larger a spot is, because it causes the same absolute area change within all sizes. This would make the fluctuation stronger for small spots, since it constitutes a larger proportion of the area.

Spot Size in $\frac{1}{10^6}$ **of the solar disc** **U+P**	**No of Spots*** **U, P, U+P > 0**
< 15	7491
≥ 15 and < 50	4308
≥ 50 and < 300	5545
≥ 300	1042

*Number of spots after having added the umbra values for spots with common penumbrae.

Table 5: *Number of sunspots in four different size groups.*

We will dig deeper into this matter by investigating the umbra-penumbra area ratio versus the umbra area.

Figure 23 shows the umbra-penumbra area ratio as a function of umbra area. We have divided the data set roughly into fluctuation minima and maxima according to Figure 14, by separating the minimum years of 1988 and 1994 from the maximum years of 1993 and 1995. In Figure 23 we see that the periodicity is caused by spots with an umbra area smaller than approximately 16 millionths of the solar hemisphere.

During minima all spots have an almost uniform umbra-penumbra area ratio, whereas spots with an umbra area smaller than 16 millionths of the solar hemisphere clearly diverge to higher umbra-penumbra values during maxima. The deviation increases with decreasing size of the umbra. There may be a tendency for small spots to have a departing umbra-penumbra ratio also during minima, but this deviation is of a much lower order than at maxima and is perhaps caused by measurement uncertainties as areas are rounded to integer values.

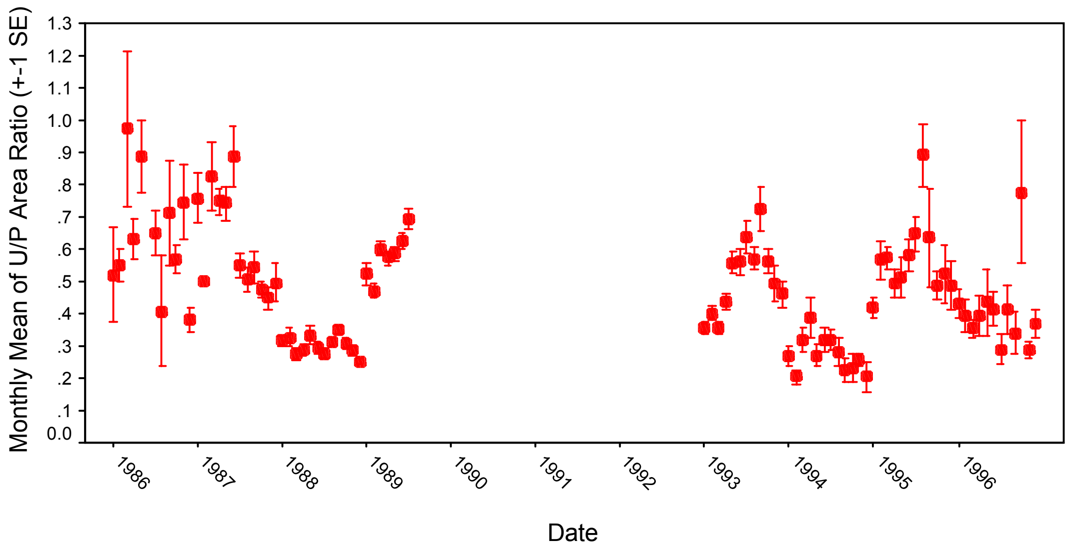

Figure 18: *Monthly mean of the umbra-penumbra area ratio for spots with corrected total area less than 15 millionths of the solar hemisphere.*

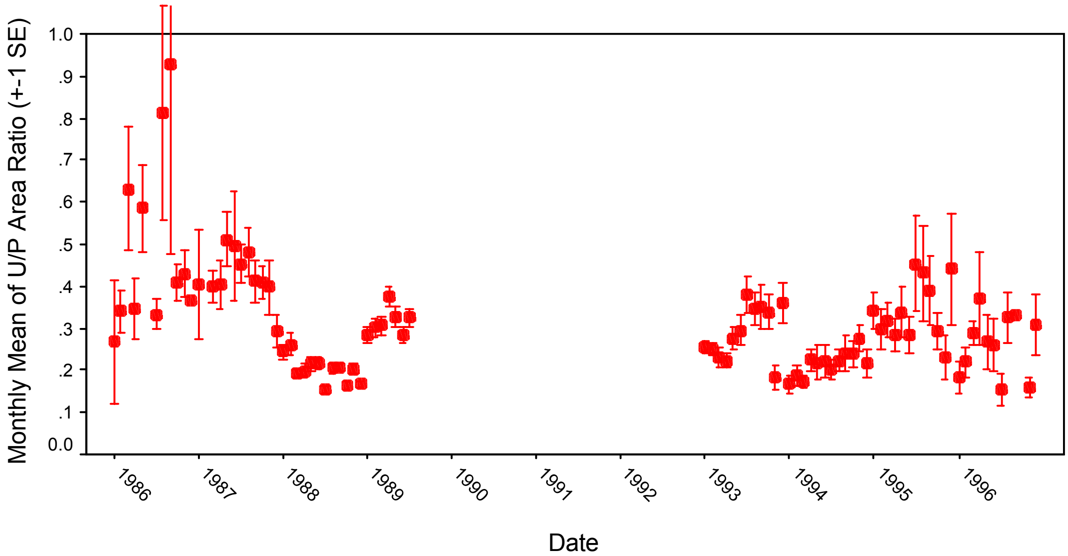

Figure 19: Monthly mean of the umbra-penumbra area ratio for spots with corrected total area equal to or larger than 15 but less than 50 millionths of the solar hemisphere.

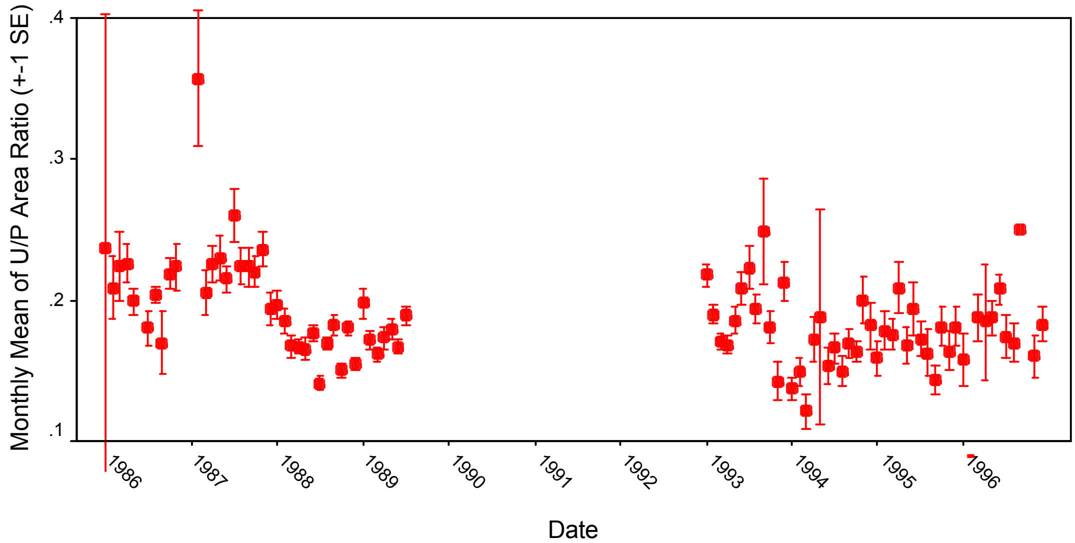

Figure 20: *Monthly mean of the umbra-penumbra area ratio for spots with corrected total area equal to or larger than 50 but less than 300 millionths of the solar hemisphere.*

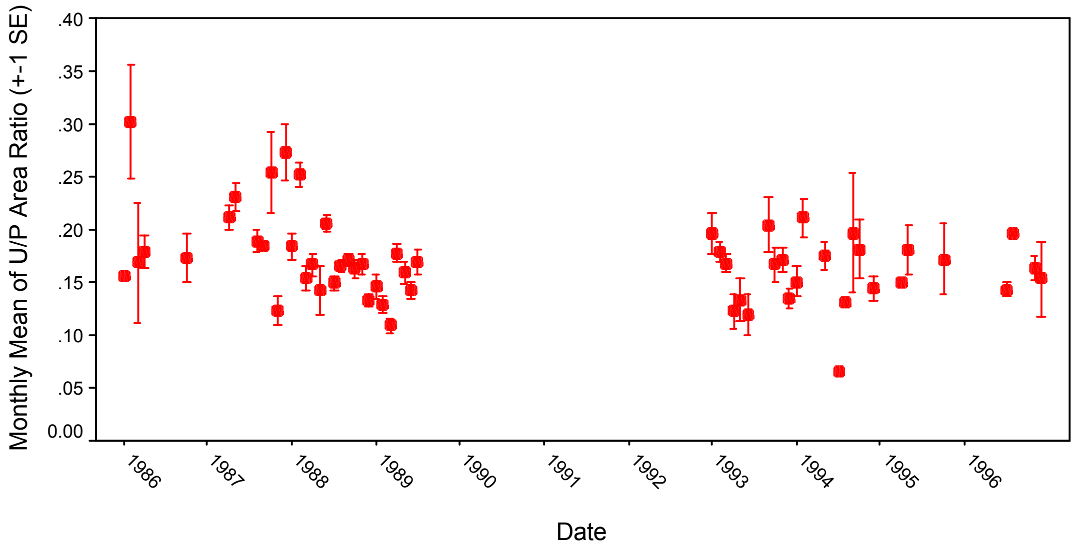

Figure 21: *Monthly mean of the umbra-penumbra area ratio for spots with corrected total area equal to or larger than 300 millionths of the solar hemisphere.*

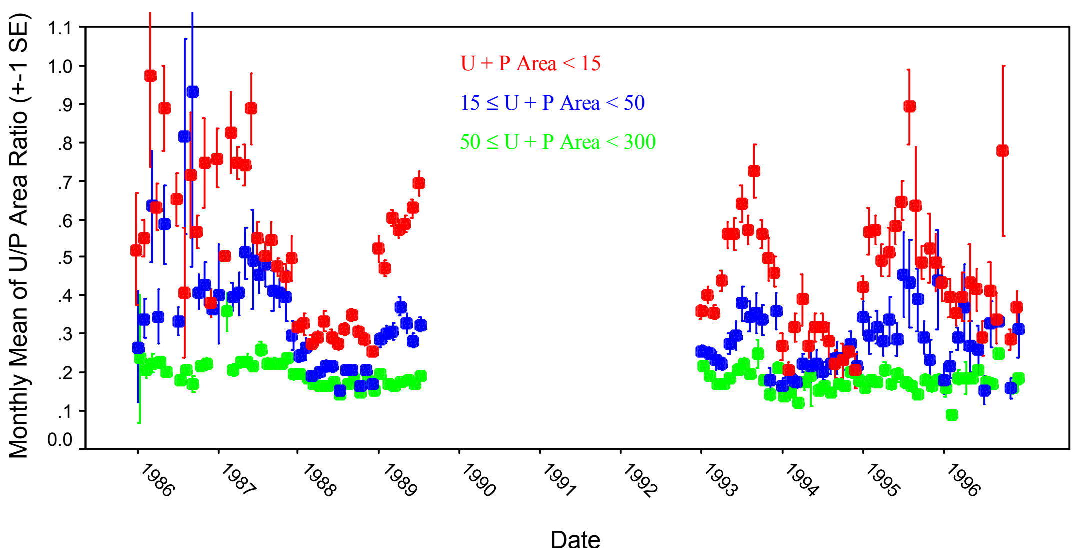

Figure 22: *Umbra-penumbra area ratio for sunspots divided into three different size-groups according to their corrected total area.*

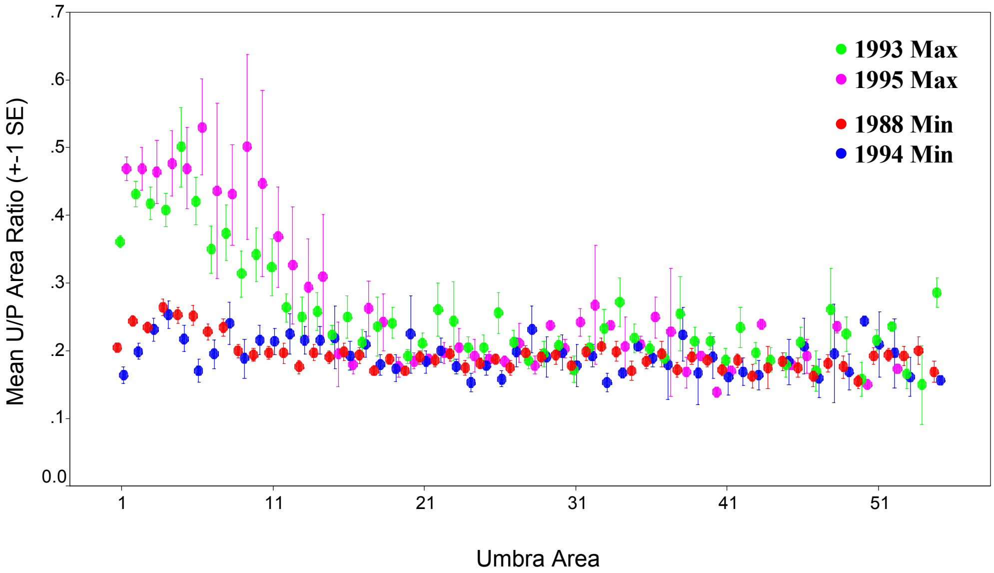

Figure 23: *The umbra-penumbra area ratio as a function of umbra area. The data set is divided roughly into fluctuation minima and maxima by separating the minimum years of 1988 and 1994 as well as the maximum years of 1993 and 1995.*

8.1.7 Sunspots with More than one Umbra or/and Penumbra Excluded

We have two choices to treat spots with common features with other spots. The choices are either to omit spots with summed penumbra values but common umbra values with other spots, or to sum the common umbra values for the spots with common penumbrae. Until now we have considered only the latter case, and now the time has come for the omitting option. In Figure 24 spots with common umbrae or/and penumbrae with one or more spots are excluded. We can establish that this procedure did not lower the spread of the 1986 data either. We have also tried to exclude whole groups if spots within them were complex, but this only reduced the amount of data without any result. We will continue to work with the summed common umbra values for the spots with common penumbrae.

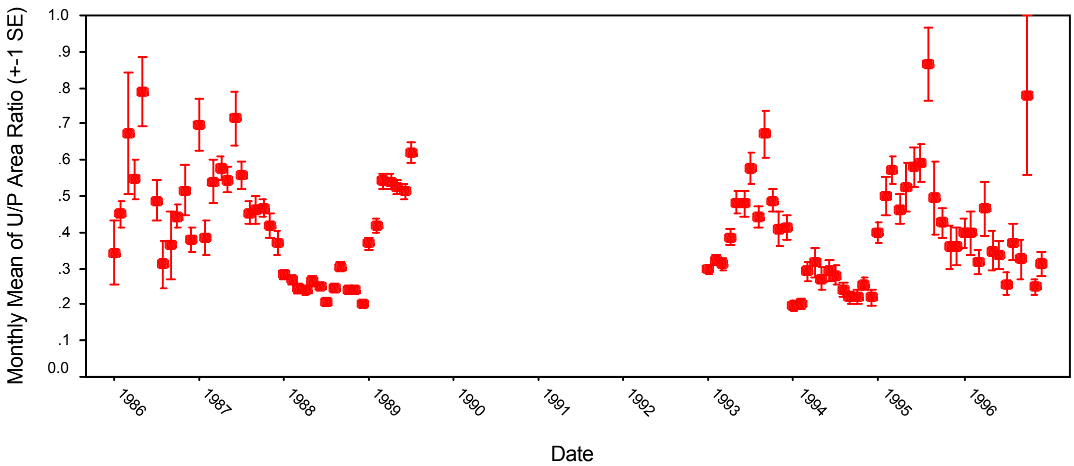

Figure 24: *Monthly mean of the umbra-penumbra area ratio for spots. Spots with more than one umbra or/and penumbra are excluded.*

We can draw the conclusion that the periodicity is not caused by a fluctuation of appearance of sunspots with more than one umbra.

8.1.8 Short- and Long-Lived Sunspots

Our next approach is to see if spots belonging to long- and short-lived sunspot groups show different behaviour. Our choice of delimiter between short- and long-lived sunspot groups is purely based on getting enough spots in the short-lived collection. If the number of spots is too low, it is very difficult to draw any conclusions since the uncertainty is large.

Figures 25 and 26 show the monthly mean of the umbra-penumbra area ratio for

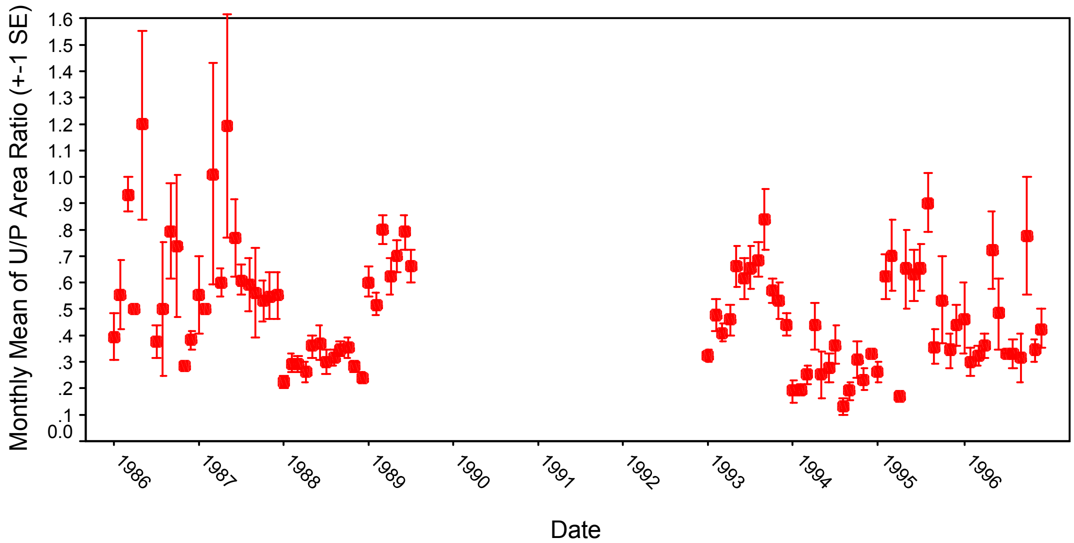

Figure 25: *Monthly mean of the umbra-penumbra area ratio for spots belonging to short-lived sunspot groups, i.e., groups that do not live longer than five days.*

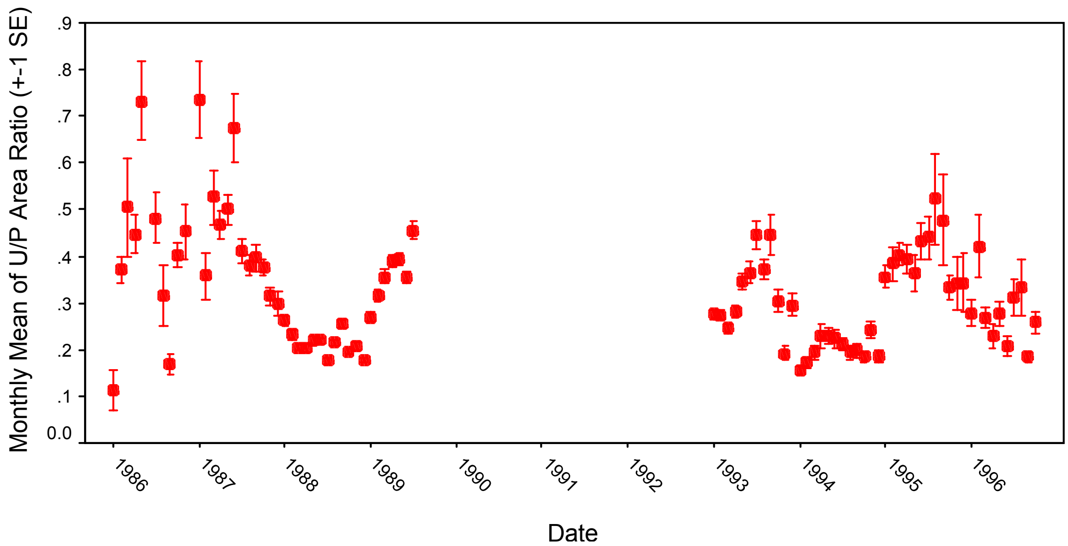

Figure 26: *Monthly mean of the umbra-penumbra area ratio for spots belonging to long-lived sunspot groups, i.e., groups that live at least six days.*

spots within sunspot groups that, respectively, do not live longer than five days or live at least six days. Both categories show a periodicity, but the short-lived spots have a higher amplitude than the long-lived. This is because the short-lived spots most often are small, i.e., this is the same phenomenon as we have seen earlier.

8.1.9 With the Second Half of the Year 1989 Included

During the course of our work, the compilation of August to November of the year 1989 was completed. We had come too far in our investigation to redo all analyses, but a plot with these months with all sunspots included, except the zero umbra or penumbra ones, is shown in Figure 27. The new mean values fit well to the plot, and continue where July 1989 left off.

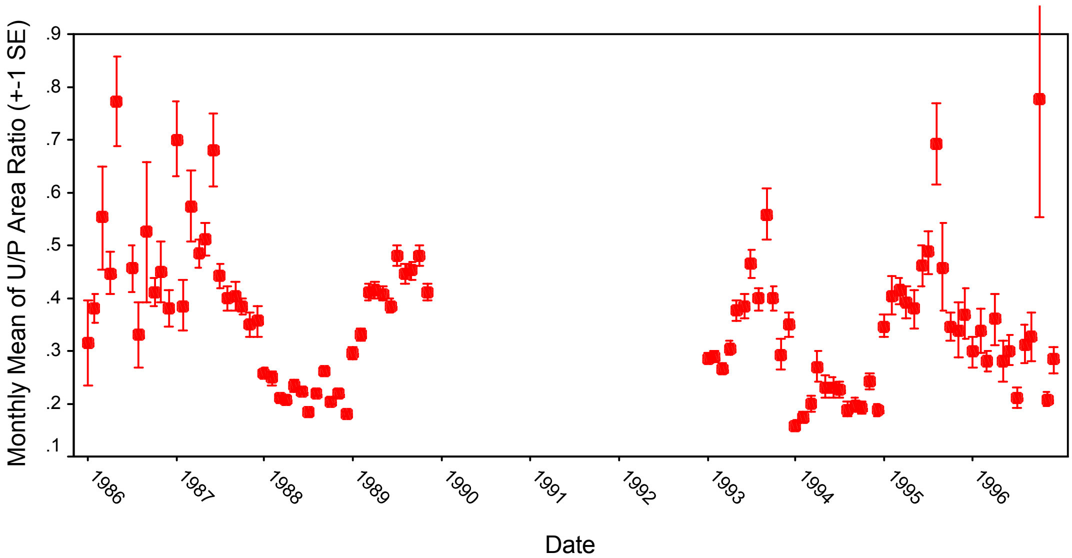

Figure 27: *Umbra-penumbra area ratio for sunspots for the years 1986 to November 1989, and 1993 to 1996.*

8.2 The Umbra-Penumbra Area Ratio for Sunspot Groups

There are some other sunspot catalogues than the DPD in which we can look for a quasi-biennial periodicity of the sunspot umbra-penumbra area ratio, the DPR (Section 4.2) and the Greenwich Catalogue (Section 4.1). The available digitized Greenwich Catalogue contains data only for sunspot groups, not for individual spots. The DPR contains data for spots, but only for spots interesting for some reason, i.e., not every spot observed. In order to compare analyses of these databases with analyses made on the DPD, an investigation of the umbra-penumbra area ratio for sunspot groups is needed.

8.2.1 The DPD

As indicated in Figure 28, the monthly mean of the umbra-penumbra area ratio for sunspot groups also shows a two-year periodicity, just like for the individual spots, but with a lower amplitude (compare Figure 14). This lower amplitude is caused by the sunspots being gathered into sunspot groups where the contributions from small spots, if any, make out a much smaller amount than the contribution from possible large spots. As described in the previous section, the amplitude of the quasi-biennial variation decreases with increasing spot size.

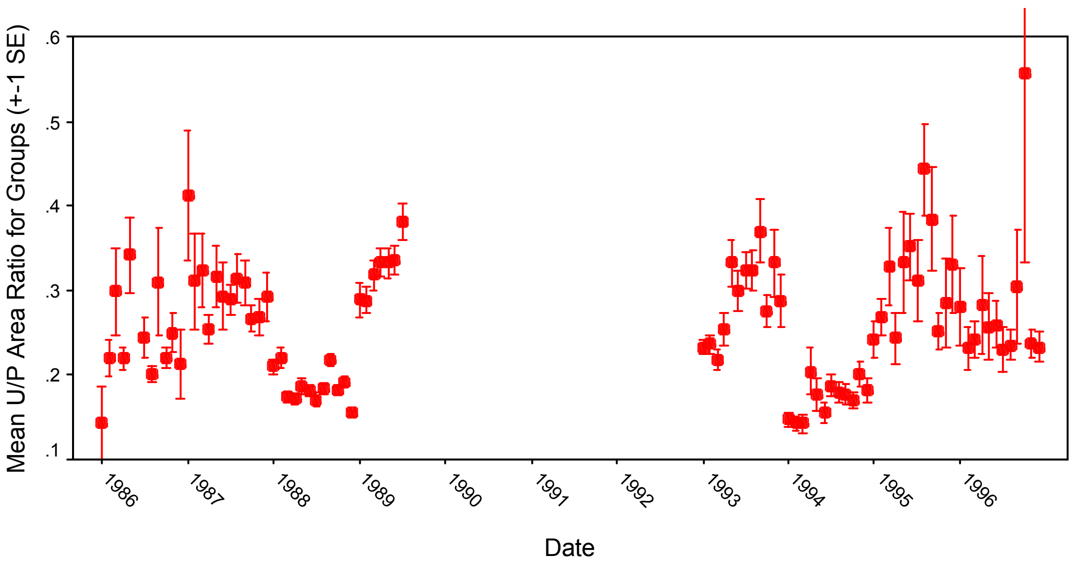

Figure 28: *Monthly mean of the umbra-penumbra area ratio for sunspot groups.*

8.2.2 Jumps in the Two-Year Periodicity

When zooming in the plot of the mean umbra-penumbra area ratio for sunspot groups, two or perhaps three jumps in the periodicity are seen. Figures 29 and 30 show the monthly mean of the umbra-penumbra area ratio for the years 1986 to 1989 and 1993 to 1996, respectively. The two clear leaps are from 1988 to 1989 and from 1993 to 1994. The change from 1987 to 1988 can also be considered as a jump, but less obvious than the two previously mentioned ones. Discontinuities in the graphs can be there naturally. The reason that these caught our eye is that the changes in all three cases are between the months December and January.

Our first thought was that perhaps the years 1988 and 1994, the ones with lower mean umbra-penumbra area ratio values than the other years, have been measured separately, but they have not. The method and chronology of the process of producing the catalogue are described in Section 3.4. The most likely explanation for jumps occurring in December and January, rather than some other time, is that the complete years are compiled more or less uniformly, but small improvements in the measuring methods and algorithms are made from year to year. These small changes can very well be the cause of the jumps, since there were no modifications whatsoever between the years 1986 and 1987, nor between 1995 and 1996, resulting in a smooth transition between the months December and January in both cases. Another reason for jumps occurring at this time of year can be that the observations made at the Earth's Northern hemisphere suffer the worst period of visibility conditions.

It is also interesting to note that the 1996 values, which are descending toward a minimum, do not reach a mean ratio as low as the minimum years 1988 and 1994 do, i.e., 0.15. On the other hand, the length of the period may vary and the lowest value is perhaps not reached until 1997.

Taking a closer look at the mean umbra-penumbra area ratio for sunspots, Figures 31 and 32, the jumps seen for sunspot groups are less obvious, but a grouping of the years can be sensed.

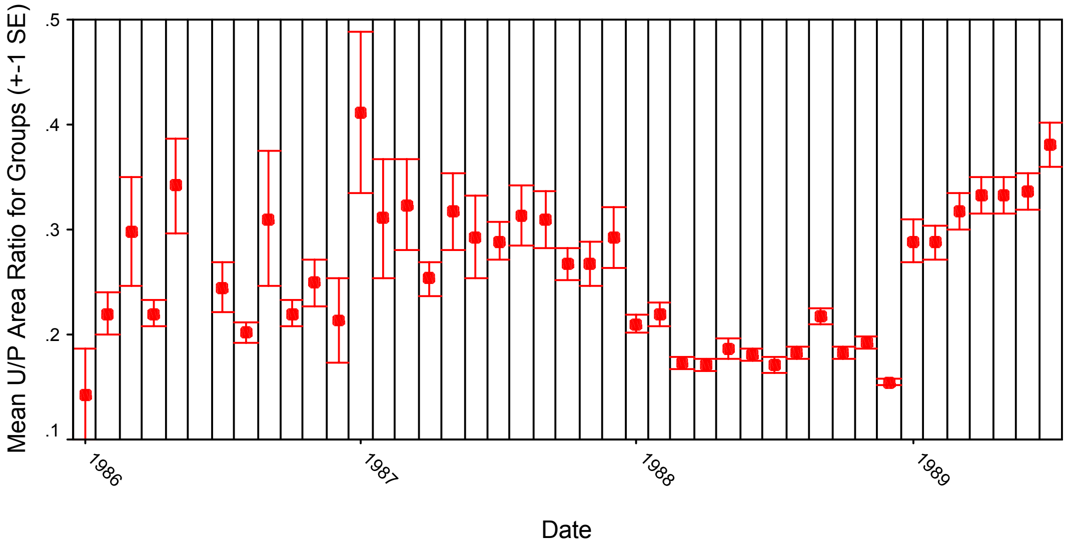

Figure 29: *Monthly mean of the umbra-penumbra area ratio for sunspot groups for the years 1986 to July 1989.*

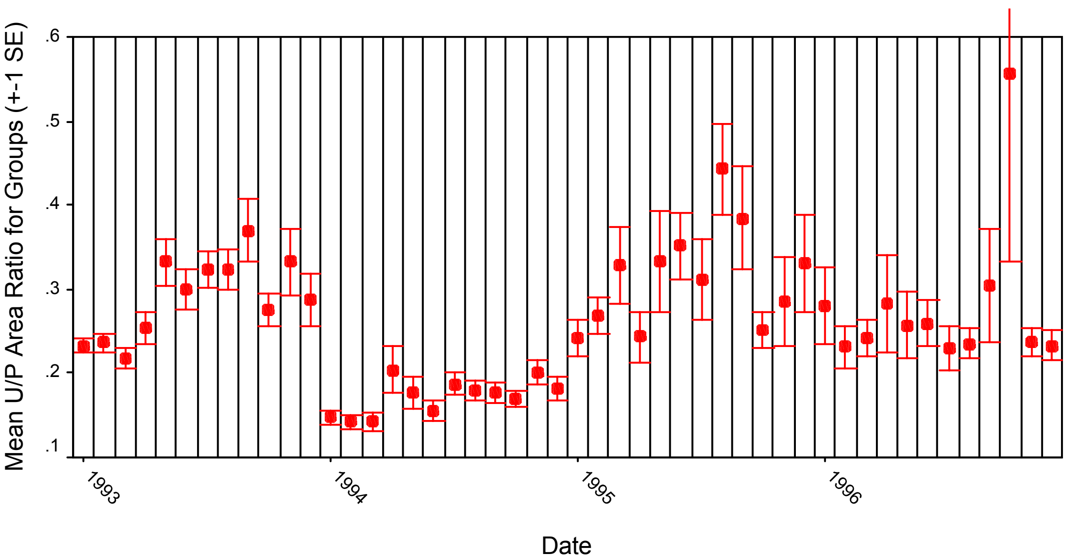

Figure 30: *Monthly mean of the umbra-penumbra area ratio for sunspot groups for the years 1993 to 1996.*

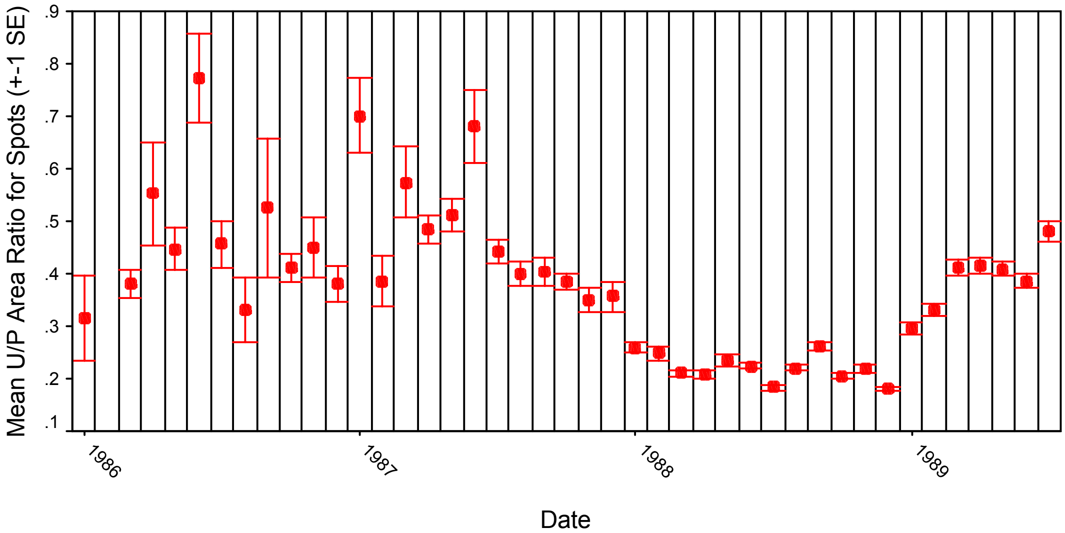

Figure 31: *Monthly mean of the umbra-penumbra area ratio for sunspots for the years 1986 to July 1989.*

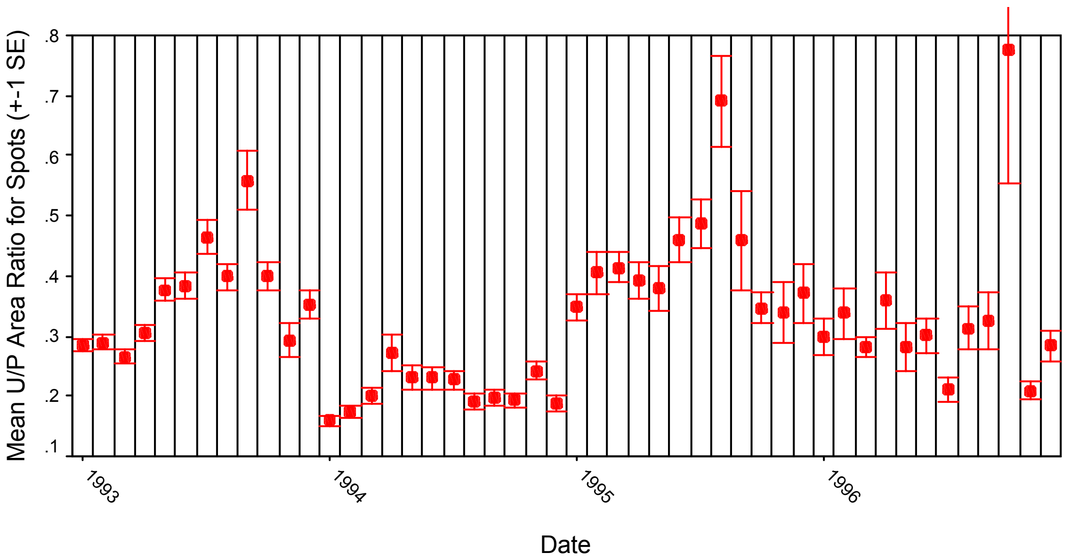

Figure 32: *Monthly mean of the umbra-penumbra area ratio for sunspots for the years 1993 to 1996.*

8.2.3 The DPR

The analyses of the monthly mean of the umbra-penumbra area ratio for sunspot groups in the DPR for the available years of 1977 and 1978 give a one-year period in the manner indicated in Figure 33. There is a discrepancy in the period when comparing the DPR to the DPD, but a consistency in amplitude. However, the shorter period in the DPR does not have to contradict the two-year period found in the DPD, since the length of the cycle may vary.

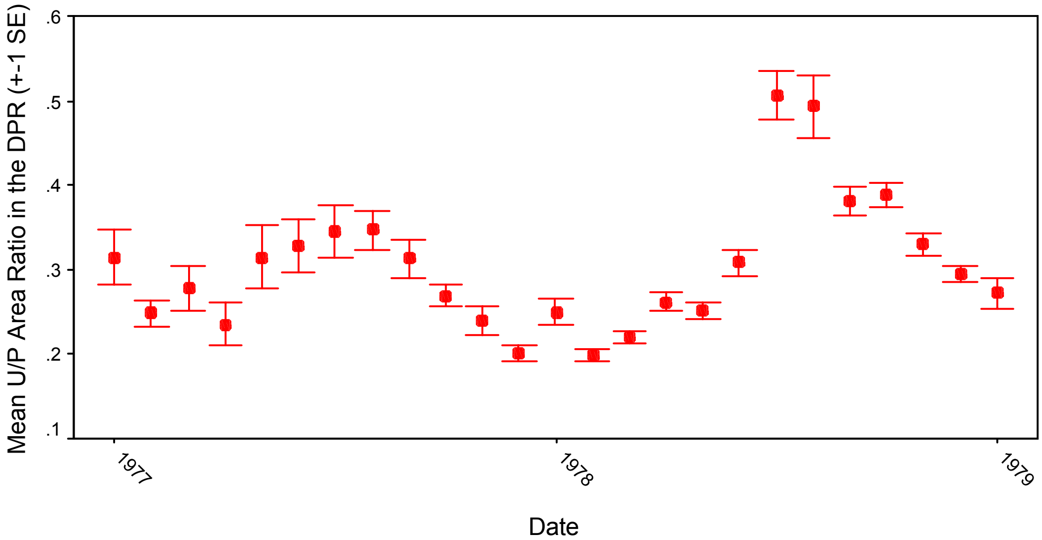

Figure 33: *Monthly mean of the umbra-penumbra area ratio for sunspot groups in the Debrecen Photoheliographic Results (DPR).*

8.2.4 The Greenwich Catalogue

We have also searched the Greenwich Catalogue for similar periodicities as found in the DPD and the DPR. Some occasional one- or two-year periods can be found, but not continuously. However, the large scatter of data and the different long-term trends prohibit to draw any conclusions.

8.3 Conclusions

The umbra-penumbra area ratio varies in what seems to be a quasi-biennial manner. Period analyses are needed to make sure and investigate this periodicity further.

We have investigated several subgroups of sunspots to find out if one or a group of them is the cause of the fluctuation. Sunspots occurring on both the northern and southern hemisphere behave similarly, sunspots sharing umbra or/and penumbra with other spots do not have an influence on the two-year periodicity, and both short- and long-lived sunspots lie on the same type of curve. The amplitude of the periodicity decreases with increasing spot size, to disappear completely for spots larger than 300 millionths of the solar hemisphere. We can draw the conclusion that this may be caused by the mechanism causing the fluctuation being more efficient on smaller than on larger spots.

We have tried to see if the spread of the 1986 data decreases by excluding sunspots close to the solar limb, dividing the spots into size groups and excluding spots with common umbra or/and penumbra with other spots, but the spread has shown to resist our attempts. The deviation from the main trend of a two-year periodicity of the 1986 and the first half of the 1987 data coincide with the change from the old area-measuring method with the Dareal. This is the most likely explanation for the sudden decrease of both the spread and the error bars.

Also the umbra-penumbra area ratio for sunspot groups in the DPD show a quasi-biennial fluctuation, but with a lower amplitude than for the sunspots. The DPR shows a one-year periodicity, but that does not have to contradict the two-year periodicity in the DPD, since the period may vary.

We did not find any quasi-biennial variation in the Greenwich data but 'the absence of evidence is not evidence of absence'[5].

[5] Said by B. Roberts, in a different context, at the NATO Advanced Research Workshop *Turbulence, Waves and Instabilities in the Solar Plasma*, Budapest, Hungary, September 2002

9 Quasi-Biennial Variations of the Sunspot Umbra-Penumbra Ratio

In this section we analyze the periodic behaviour of the DPD umbra-penumbra area ratio.

9.1 Spectral Analysis of the Umbra-Penumbra Area Ratio Fluctuation

There are several different methods of investigating the spectral contents of a discrete signal. With the help of Matlab, we have analyzed the periodic behaviour of the umbra-penumbra area ratio fluctuations found in the DPD, by estimating its power spectral density (PSD) using periodogram. The two different time intervals, 1986 to 1989 and 1993 to 1996, have been treated separately since the fast Fourier transform (FFT) requires a sampled signal without gaps to give an accurate result. The samples used are for the sake of simplicity the monthly means with all sunspots included, as presented in Section 8.1.2. The error introduced by the varying sample interval (due to varying number of days in the months of the year) is small in comparison with the crudity of probing a quasi-biennial signal in a four-year long data set. The highest analyzable frequency has a period of twice the sampling period, according to the Nyqvist sampling theorem. A higher sampling frequency than of the order of one month is not suitable for this data set since the number of gaps increases fast with shorter averaging intervals. As we are interested in deducing the characteristics of a quasi-biennial period, the frequency range from zero to six cycles per year is enough. In place of the one and only missing monthly mean of May 1986, the mean of the two neighbouring monthly values is used due to the need of a consistent time series.

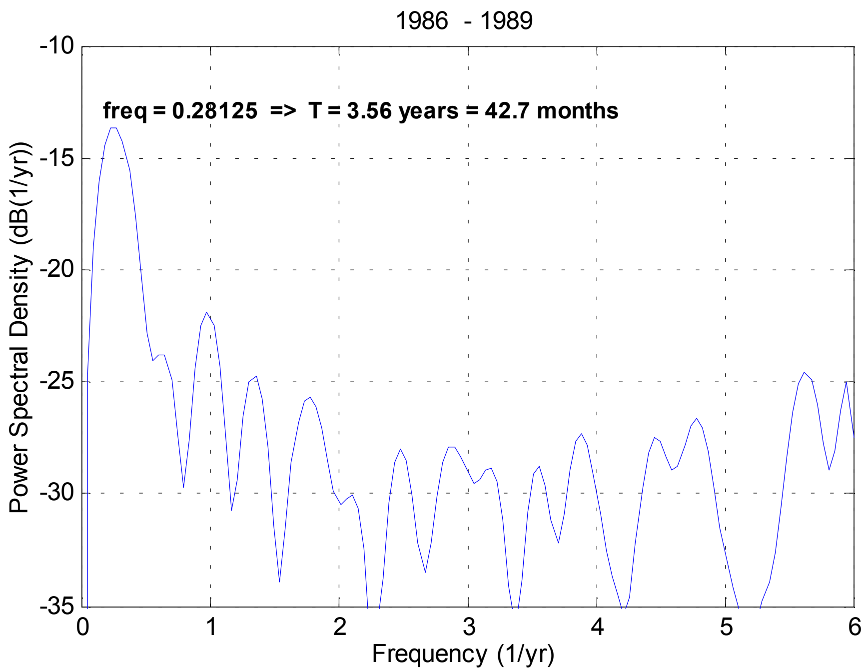

Figure 34: *PSD estimate for the monthly mean series of the umbra-penumbra area ratio for 1986 to 1989. We have centred the observed fluctuation around zero by subtracting the mean value prior to analysis.*

In Figure 34 the PSD estimate for the 1986 to 1989 time interval can be seen, and in Figure 35 the estimate for 1993 to 1996. The mean umbra-penumbra area ratios of the intervals have been subtracted from the two sets of monthly values, respectively, to center the data around zero and only reveal their periodic behaviour. The spectral peaks are broad due to the shortness of the data sets as discussed previously, but we are able to make rough estimations for their frequency contents.

The 1986 to 1989 data set has their highest spectral peak at a frequency corresponding to a period of almost 43 months. This can be visualized by fitting an imagined sinusoidal curve with a 43-month-period to the minimum of 1988 and the high monthly values of 1986 and early 1987 in Figure 14 in Section 8.1.2. This curve would have a very high amplitude compared to any more rapidly varying curve fitted to the low values of 1986 and therefore also have higher energy density. The peak is broadened in the sense of shorter periods and has a bump at a frequency corresponding to a period of about 20 months. Since the data of 1986 and the first half of 1987 are more spread than the monthly averages of the following years we find the period of 43 months untrustworthy. The broadening of the peak towards shorter periods and the bump are signs of a quasi-biennial signal with a shorter period than 43 months.

The 1993-1996 spectral analysis in Figure 35 has its highest spectral peak at a frequency corresponding to approximately 21 months. This peak has a lower absolute value than the highest peak of Figure 34 and is broadened in the sense of longer periods. There is a local minimum limiting the peak to periods longer than one and a half years. In both Figure 34 and Figure 35 there are significant peaks also at a frequency corresponding to exactly one year. This might be a sign of observational seasonal effects since the period of one Earth-rotation around the Sun is not expected to appear in a feature of solar origin.The Earth's contribution to the angular momentum of our solar

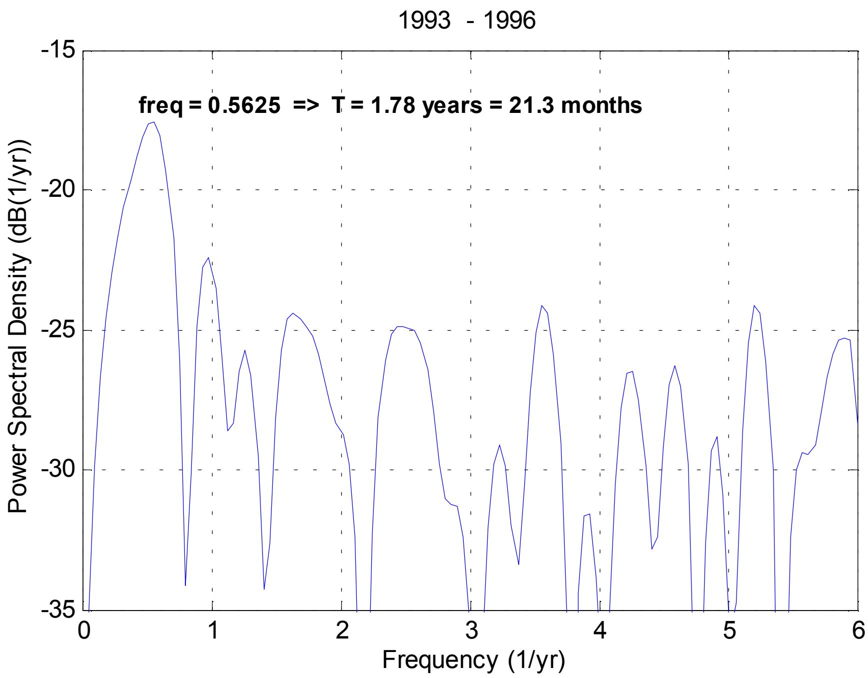

Figure 35: *PSD estimate for the monthly mean series of the umbra-penumbra area ratio for 1993 to 1996. We have centred the observed fluctuation around zero by subtracting the mean value before the analysis.*

system is negligible, and we are not aware of any other way a planet can influence the Sun such that a solar periodicity with a period equal to the period of revolution of the planet is produced.

9.2 A Bridge Over the Gap?

If we, in spite of the different periods found by spectral analysis in Section 9.1, consider the fluctuation as having a more or less constant length of its cycle as it progresses in time, we should be able to fit the two data sets with a single sinusoidal curve. This curve is a prediction of what the umbra-penumbra area ratio can be expected to be in the gap between the data sets. We have made a non-linear regression analysis with SPSS by assuming a model with four free parameters according to the formula

$$U/P = C + A \cdot \sin(\omega \cdot time + \phi)\,, \tag{9}$$

where the umbra-penumbra area ratio (U/P) versus time (in years) is modelled by an arbitrary constant C added to a sinusoidal function with arbitrary amplitude A, angular frequency ω and phase ϕ.

Parameter	**Value**	
Constant (C)	0.3157	
Amplitude (A)	0.1106	
Frequency (ω)	3.117	yr^{-1}
Phase (ϕ)	1.80	rad
Period ($\frac{2\pi}{w} \cdot 12$)	24.2	months

Table 6: *Parameter values for the best sinusoidal fit of the monthly mean U/P area ratio of sunspots in the DPD.*

The parameter values found in Table 6 are, with the exception of the phase, presented with four significant digits. The digits are significant in the sense that they are non-changing under different, reasonable starting assumptions. For enabling use of the Levenberg-Marquardt algorithm implemented in SPSS no constraints can be put on the parameters. Without constraints, the phase can assume any value with a multiple of 2π added to its fundamental value between 0 and 2π, still giving an identical solution. Thus, different starting conditions give different values for the phase. The value for the phase presented in Table 6 is found by subtracting any multiples of 2π and correcting with π if the amplitude is negative. (The multiple *can* contain an odd number of π for an identical solution, but in this case the corresponding amplitude found by the algorithm is negative.)

The model described in Table 6 is illustrated in Figure 36. It can be seen that the sinusoidal curve with a period of 24.2 months quite well fits the data with exception of the year 1986 and the first half of 1987. This might be due to the non-fitting data not being reliable, the cycle length of the periodicity varying, or, most likely, a combination of these two features.

9.3 Variation of the Cycle Length?

There are many different solar mid-term periodicities found during the last decades, for example, the solar neutrino flux measured by the Homestake experiment and a shear oscillation of the solar tachocline region. For further information, see [Ke03]. Some of

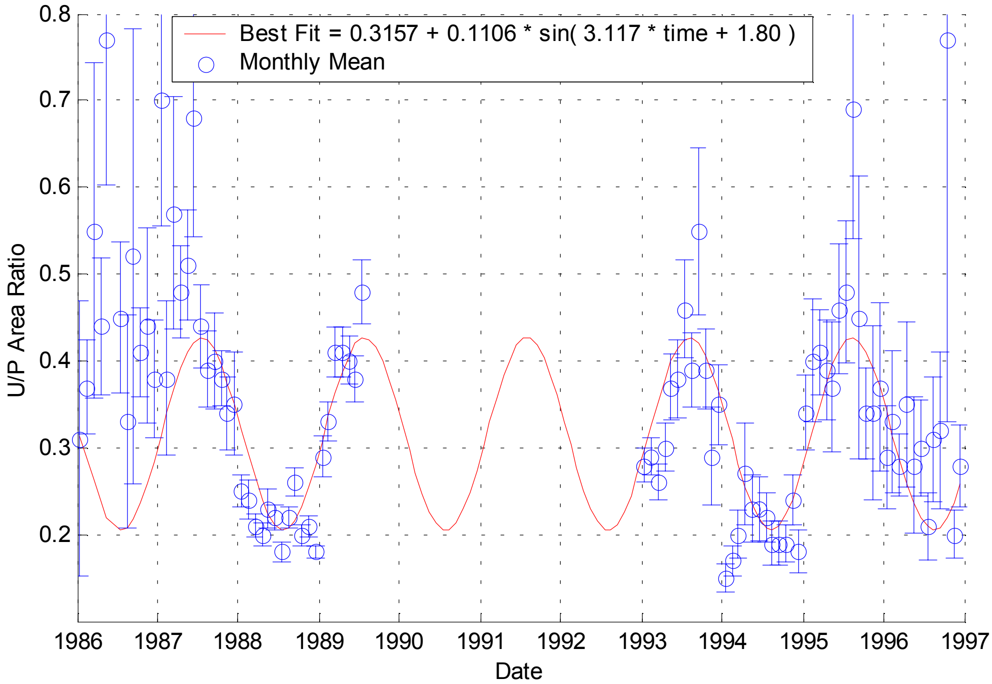

Figure 36: *Monthly mean of the umbra-penumbra area ratio for sunspots and the best sinusoidal fit found by nonlinear regression with SPSS. The error bars correspond to two standard errors.*

these periodicities are less well-established than others, but even the most well-known seem to have an evolving cycle length. The main eleven-year sunspot cycle has also been varying between less than ten to an almost twelve years length during the last 140 years [La00], for which reliable observations have been done.

The behaviour of many discovered phenomena of our star are as dynamic as the way they reveal themselves, like the gigantic outbursts of coronal mass ejections. There is no reason to expect a complete regularity in the case of an umbra-penumbra fluctuation, even though the appearance of sunspots in the photosphere observed in white-light is a quite quiescent phenomenon.

To be able to reveal the main trends of the cyclic behaviour of the umbra-penumbra area ratio, we have treated the two data sets separately and fitted each of them with least-square-methods in Matlab. The data series are first normalized according to

$$\hat{X} = \frac{U/P - \mu_1}{\mu_2}, \tag{10}$$

where $\hat{X}$ is the normalized data, U/P the original data, μ_1 the mean value and μ_2 the standard deviation. Then a least-square fit is made whereafter the fitted curve is transformed back with the inversion of Equation (10) to enable comparisons with the original data. We have by inspection found a polynomial degree of six to be suitable for the curves to show the quasi-biennial trend as clearly as possible, but not contain faster variations similar to the scatter of the original data.

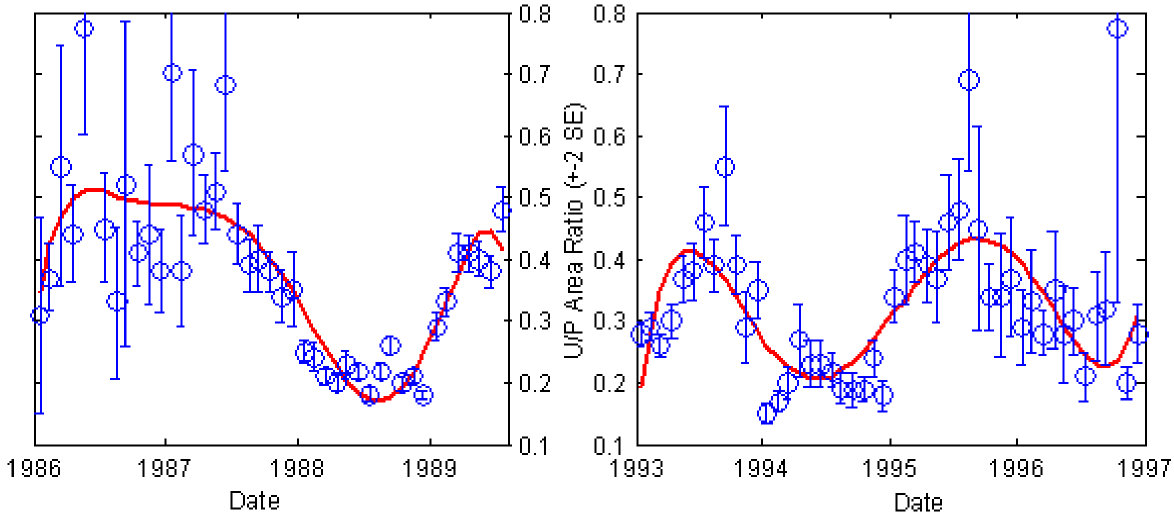

Figure 37: *The monthly mean umbra-penumbra area ratio fitted with polynomials of degree six.*

Plots for both time intervals are shown in Figure 37. The data from 1986 and the first half of 1987 may be uncertain, as discussed previously. The monthly mean of October 1996 has not been taken into account when fitting polynomials to the time interval 1993 to 1996 since it has large error bars but due to its deviant value strongly influences the polynomial fit.

It can be seen in Figure 37 that the cycle length may be shorter close to activity maximum (i.e., near the gap between the data sets) than at lower activity periods however, the amplitudes of the polynomial curves are rather uniform.

9.4 Conclusions

Since the intervals of available data are short compared to the cycle length of the fluctuation, it is at this moment difficult to conclude anything else than that the variation has a period that may vary from 1.5 to 3 years or more depending on how much confidence one has in the data of 1986 and the first half of 1987.

10 The Future

In a way the future is already here. This section says in what way.

10.1 The Future of the DPD at the Debrecen Heliophysical Observatory

In early December 2002, a grant was approved for a new high-resolution scanner to be bought. This will speed up the production of the DPD series because it will be possible to scan photoheliograms in one piece, with a very good resolution. There will be no need of separate position and area measurements, as described in Section 3.3. Both can be carried out at the same time. When the software to be used is fully developed and calibrated, it will be a powerful tool. The umbra and penumbra areas will still be manually checked, but the complete process will be faster and easier, due to fewer steps and the data will contain even less errors than they do today.

10.2 The Future of the Quasi-Biennial Variation of the Sunspot Umbra-Penumbra Area Ratio

A two-year period seems to be present in the sunspot umbra-penumbra area ratio for the DPD. Further analyses of more data will be very interesting. With the quicker compilation of the DPD catalogue, the possibility of an extended investigation is not far in the future. Since the periodicity we have found is very exiting, it will not be forgotten. A scientific article on the subject is planned.

Appendix A

Table of Photoheliograms in the DPD

Table 7 contains the number of photoheliograms used in the DPD from the different contributing observatories around the world.

Observatory	**No. of Plates**
Gyula Observing Station (Hungary)	1644
Debrecen Heliophysical Observatory (Hungary)	576
Kislovodsk Observing Station of Pulkovo Observatory (Russia)	268
Kanzelhöhe Solar Observatory (Austria)	129
Ramey, Puerto Rico (U.S.)	40
High Altitude Observatory, Boulder (U.S.)	25
Kodaikanal Solar Observatory (India)	9
Ebro Observatory (Spain)	7
Helwan Solar Station (Egypt)	6
Tashkent Observatory (Uzbekistan)	6
Kiev Universtiy Observatory (Ukraine)	5
Abastumani Astrophysical Observatory (Georgia)	3
Holloman (U.S.)	3
Mount Wilson Observatory (U.S.)	2
$\sum$ 14	$\sum$ 2723

Table 7: *Number of photoheliograms from around the world used in the DPD for the years 1986 to July 1989 and 1993 to 1996.*

Appendix B

Table of the Number of Sunspots in Different Investigations

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Criteria	**No. of Spots*** **U, P, U+P > 0**
In total	18386
Where U of groups is maximal	3234
Distance < 0.9 solar radii from the centre of the solar disc	15174
Spots with common features with other spots excluded	10989
Short-lived spots ($\leq$ 5 days)	1899
Long-lived spots (> 5 days)	16487

*Number of spots after adding the umbra values for spots with common penumbrae.

Table 8: *Number of sunspots in the DPD used in different investigations for the years 1986 to July 1989 and 1993 to 1996.*

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