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Solar Observations by Angelo Secchi. I. Digitization of Original Documents and Analysis of Group Numbers over the Period of 1853–1878

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Abstract

Angelo Secchi, an Italian Jesuit and prominent scientist of the 19th century, and one of the founders of modern astrophysics, observed the Sun regularly at the Collegio Romano in Rome, Italy, for more than 25 yr. Results from his observations are reported in articles published in the scientific journals of the time, as well as in drawings and personal notebooks that are stored in the historical archive of the Istituto Nazionale di Astrofisica Osservatorio Astronomico di Roma. The latter material, which reports solar observations performed from 1853–1878, includes original documents from Secchi and from a few of his close collaborators. The above unique material has recently been digitized for preservation purposes and for allowing the scientific exploitation of data not easily accessible so far. A total of more than 5400 digital images have been produced. Here we present the archival material and the new digital data derived from it. We also present results obtained from our primary analysis of the new digital data. In particular, we produced new measurements of the group number from 1853–1878, which will be available for future recalibration of the group number series.

Unified Astronomy Thesaurus concepts: Sunspot groups (1651)

Supporting material: machine-readable table, tar.gz file

1. Introduction

Regular monitoring of the solar surface performed with telescopes has been carried out since the early 17th century when Galileo Galilei, Thomas Harriot, Christoph Scheiner, and their contemporaries performed the first telescopic sunspot observations (e.g., Galilei 1613; Scheiner 1630; Herr 1978; Neuhäuser & Neuhäuser 2016; Arlt & Vaquero 2020; Carrasco et al. 2020, 2022; Vokhmyanin et al. 2020). These early observations (Vaquero & Vázquez 2009) revealed that the Sun has sunspots, which move across the solar disk due to the solar rotation. Systematic observations later displayed that the number of sunspots has an approximately 11 yr cyclic variation known as the *solar cycle* (Schwabe 1843; Karoff et al. 2019). Besides, continued monitoring of sunspots showed that their latitudinal distribution varies along the solar cycle (Maunder 1904), with sunspots appearing at progressively lower latitudes toward the end of a cycle (Hathaway 2015).

Sunspots are the most prominent manifestation of the Sun's magnetic field (Hale 1908; Solanki 2003; Vaquero 2003; Hayakawa et al. 2020) in the visible layers of the solar atmosphere known as the solar surface or photosphere. There, the magnetic field also manifests itself as dark pores and bright faculae, while at greater heights in the solar atmosphere, in, e.g., the chromosphere, it forms bright plages (Chatzistergos et al. 2022) and network features, and dark filaments, evident at the radiation of the H_α and Ca II K lines at 656.3 and 393.4 nm, respectively (Stix 2004; Solanki et al. 2006). The latter appear as bright prominences when seen protruding far out of the solar disk (Parenti 2014), as well as small-scale jets known as spicules.

Regular observations have shown that the number of all the aforementioned Sun's features follow the rise and decay of the solar cycle (see, e.g., McIntosh et al. 2021; Carrasco et al. 2022), as it is for the occurrence of Sun's eruptive events, also linked to the magnetic field, such as flares (Hudson et al. 2014) and coronal mass ejections (Gopalswamy 2006; Webb & Howard 2012; Hayakawa et al. 2022b). In addition, the solar cycle also characterizes the electromagnetic (e.g., Domingo et al. 2009; Ermolli et al. 2013; Yeo et al. 2014; Chatzistergos et al. 2023) and particle (e.g., Vainio et al. 2009; Desai & Giacalone 2016; Miyake et al. 2019; Sinnhuber & Funke 2020; Usoskin et al. 2020; Cliver et al. 2022) emissions of the Sun.

The different solar observables linked to the magnetic field are commonly represented by a variety of indices (Ermolli et al. 2014), most notably those based on measurements of sunspots' properties (Clette et al. 2023; Usoskin 2023), e.g., the sunspot number, the group number, and the sunspot area (SA). We set out in more detail below how these different indices are linked to observed sunspots' properties and what data are there, since we will use them in the following. Note that in the above indices, thus also in our study, no distinction is typically made between sunspots and pores.

The sunspot number (S_N, according to the nomenclature in Clette et al. 2015) indicates a weighted estimate of individual sunspots and sunspot groups observed with a visual inspection of the photosphere in the white-light radiation. Compiling a series of such measurements was started by Johann Rudolf

Wolf in the middle of the 19th century in Zürich, and for this reason, it is also known as the Zürich or Wolf relative sunspot number series (see, e.g., Friedli 2016; Clette et al. 2023). However, it was extended for several solar cycles back in time by using available data from earlier observations, and continued until the present day by the Sunspot Index and Long-term Solar Observations (SILSO[7]) program at the Royal Observatory of Belgium (Clette et al. 2007, 2014; Clette & Lefèvre 2016; Clette et al. 2023). The current S_N series goes back to 1818 with daily cadence, while monthly and annual values are available back to 1749 and 1700, respectively.

The group sunspot number (G_N, according to the nomenclature in Clette et al. 2015 for new group number series) was introduced by Hoyt & Schatten (1998) as an alternative to the sunspot number index, that accounts only for sunspot groups. Significant corrections and updates applied to the group counts by Hoyt & Schatten (1998) over the years (e.g., Vaquero et al. 2016; Clette et al. 2023, and references therein) led to the publication of new G_N series (see, e.g., Svalgaard & Schatten 2016; Usoskin et al. 2016; Chatzistergos et al. 2017; Willamo et al. 2017; Usoskin et al. 2021; Clette et al. 2023) that differ also in their extent and cadence. For example, the group number series by Chatzistergos et al. (2017) extends back to 1739 with daily values,[8] the one by Usoskin et al. (2021) goes back to 1749 with monthly cadence, while the series by Hoyt & Schatten (1998) and Svalgaard & Schatten (2016) extend back to 1610 with daily and annual cadence, respectively. However, the scarcity of group number data in several decades before 1750s (see Figure 8 in Clette et al. (2023) and Hayakawa et al. (2022a) over the most problematic period in 1727–1748) along with the various criticisms that have been raised about the methodologies used by Hoyt & Schatten (1998) and Svalgaard & Schatten 2016 render the pre-1739 group number values uncertain (Lockwood et al. 2016; Usoskin et al. 2016; Clette et al. 2023).

SAs were recorded by the Royal Observatory in Greenwich (RGO; from 1874–1976; Willis et al. 2013), the Kodaikanal (from 1904–2017; Jha et al. 2022), and Madrid (from 1914–1986; Aparicio et al. 2014) observatories, and for shorter periods also by other observatories, e.g., Valencia (from 1920–1928; Carrasco et al. 2014), Coimbra (from 1929–1941; Carrasco et al. 2018), Pulkovo (from 1932–1991; Gnevysheva 1968), Kislovodsk (from 1952–2018; Nagovitsyn et al. 2017), Rome (from 1958–2020; Cimino & Torelli 1978), and Debrecen (from 1974–2018; Győri et al. 2017). Among them, the Debrecen Observatory took on the task of continuing the RGO series. Besides, Balmaceda et al. (2009) and Mandal et al. (2020) produced two composite series that combine measurements from several sites. The latter series includes values of SAs with daily cadence back to 1874. SAs over earlier periods have also been derived (Arlt & Vaquero 2020), but these data are significantly more uncertain and fragmented than the ones available after 1874. Uneme et al. (2022) by using a statistical approach showed that the SAs from two observers in the early 1800s, during the Dalton minimum, (Thaddäus Derfflinger and Stephan Prantner) have been grossly oversized. In this context, Carrasco et al. (2022) also showed that SAs recorded by Cornelis Tevel during the period of 1816–1836, including the Dalton minimum, should be used with caution for scientific purposes because they are exaggerated on the basis of a few examples.

It is worth noting that the above sunspot indices are derived from an analysis of solar observations carried out across many years by a large number of observers. These observational data comprise drawings, tabulations, and annotations made during visual solar monitoring performed since the invention of the telescope, as well as photographs of the solar atmosphere stored on plates and films since the 1870s, and on digital formats from the 1980s onward. Among all the available data, the historical observations provide direct evidence of the Sun's past and are thus very important for improving our knowledge of the solar processes over long timescales. Besides, historical solar observations store information that find application in stellar astrophysics and in the studies of the impact of solar activity on planetary atmospheres and environments (see, e.g., Hayakawa et al. 2019, 2023). Their importance thus exceeds solar physics. In this light, the last two decades have attested significant novel work aiming to recover and exploit historical solar data, see, e.g., Clette et al. (2016) for recent studies of sunspot data, and Arlt & Vaquero (2020) and Chatzistergos et al. (2022) for recent reviews on sunspots and plages observations, respectively. In fact, the recovery of yet unexplored historical observations allows the provision of data for periods with the scarcity of information, as well as advances in the compilation of all the available data (see, e.g., Clette et al. 2023). Under this framework, a valuable data set that has only fragmentary been studied so far is the one realized by Angelo Secchi.

Angelo Secchi (1818–1878), an Italian Jesuit and prominent scientist, is considered one of the founders of modern astrophysics since the current spectral classification of stars relies on his early work on this topic (Hearnshaw 1989; Chinnici 2019). Besides, Secchi made important contributions toward understanding the phenomena observed on the Sun. Indeed, he was highly interested in solar physics and carried out a program of observations of the solar disk at the Collegio Romano Observatory in Rome (Italy) for more than 25 yr. The results of his observations are recorded in drawings and notebooks that are stored in the historical archive of the Istituto Nazionale di Astrofisica (INAF) Osservatorio Astronomico di Roma (OAR, Monte Porzio Catone, Italy). This material, hereafter referred to as the Secchi collection, includes drawings and data from solar observations performed by Secchi and his close collaborators and assistants. Find more details in the following.

In a digitization program of the INAF heritage archives, almost all documents of the Secchi collection have recently been digitized for preservation and scientific exploitation. In this paper, we describe the archival material and the digital data derived from it. We also present results from our processing of the digitized data, in particular the results from our counting of the sunspot groups in Secchi's drawings of the full-disk solar surface.

This paper is structured as follows. Following this introduction, Section 2 gives a brief biographical note on Angelo Secchi and an outline of his observations and instruments. Section 3 describes the Secchi collection and the methods applied to digitize it. Section 4 presents the results from our primary analysis of the obtained digital data. A summary and main conclusions of this work are given in Section 5. Table 1 shows the daily values of the group numbers

[7] http://sidc.oma.be/silso/

[8] Available at https://www2.mps.mpg.de/projects/sun-climate/data/ch_gsn_d.dat.

Table 1
Daily Values of Group Sunspot Numbers from Our Study

Year	Month	Day	Hour	Minute	Date	JD	G_N	Flag
1853	07	11	11	00	1853.5285	2398046.0	06	d
1853	07	12	00	00	1853.5300	2398046.5	07	d
1853	07	13	09	20	1853.5338	2398047.9	07	d
1853	07	15	00	00	1853.5382	2398049.5	04	d
1853	07	19	00	00	1853.5492	2398053.5	03	d
1853	07	31	00	00	1853.5821	2398065.5	01	d
1853	08	05	00	00	1853.5942	2398070.5	03	d
1857	05	17	10	20	1857.3782	2399451.9	05	d
1857	05	27	00	00	1857.4045	2399461.5	01	d
1857	06	02	09	30	1857.4204	2399467.9	01	d

Notes. Source specifies whether the group sunspot number G_N was derived from drawing (d) or annotation (a). Hour 00 means that there is no time information.
(This table is available in its entirety in machine-readable form.)

derived from our study, and information about the annotations in the drawings that are relevant to our analysis of the data.

2. Angelo Secchi

Due to his rich personality and important results achieved from his research work, Secchi's life and outstanding results are described in many sources (for recent reviews, see, e.g., Altamore & Maffeo 2012; Chinnici 2019, 2020; Chinnici & Consolmagno 2021). Here we briefly sketch the main aspects of Secchi's life and research to put the following discussion of our study in context.

Angelo Secchi (Reggio Emilia 1818 June 28—Rome 1878 February 26) was a Jesuit of the Collegio Romano (Rome, Italy) with an excellent background in physics and strong and novel scientific interests in the fields of astronomy, solar physics, meteorology, oceanography, geology, and geodesy. His stunning scientific ability was already clear at an early age. From 1844–1850, together with the theological formation, Secchi boosted his scientific interests with sound study, acquaintances with scientists of his time, and two short but significant sojourns abroad, as a political refugee. Indeed, following events related to the Revolutions of 1848, Pope Pius IX ordered the Jesuits to leave Italy. Due to this, Secchi, with other confreres, went into exile (Chinnici 2019) at Stonyhurst College (United Kingdom) and later at Georgetown University (Washington DC, USA). Once the ban on Jesuits was lifted, he would return to Rome in 1849. Right after, Secchi was appointed director of the Observatory of the Collegio Romano, a position he retained from 1850 until his death in 1878.

In his role as director, Secchi began the planning and construction of the new Observatory of the Collegio Romano, which was built in 1852 on the rooftop of the St Ignazio church in Rome. At this observatory, Secchi conducted outstanding astrophysical research, while he was also involved in the development of novel instrumentation and methods.

Secchi was especially interested in the Sun, which he observed on a daily basis for more than 25 yr with the help of some close collaborators and assistants. This activity led to regular recording of the results from his observations in drawings, in a series of measurements of the properties of the features observed on the solar disk, and in novel knowledge of the Sun that Secchi summarized in the book *Le Soleil* (Secchi 1870). This book underwent two editions and several translations attesting to it being one of the most successful and beautiful treatises of solar physics of the 19th century.

Key aspects of Secchi's advancement of knowledge of the Sun is the understanding of a link among the diverse features observed on the solar disk, and of solar-terrestrial phenomena, including magnetic disturbances and aurorae on Earth; see, e.g., Berrilli & Giovannelli (2022), Hayakawa et al. (2019, 2023) for recent studies including Secchi's observations. Secchi also observed some total and partial solar eclipses and took early photographs of the totality phases, which in 1860 led to primary photographic observations of the solar corona (Secchi 1860). From these observations, it was proven that the corona and prominences observed during the eclipse are real solar phenomena, not optical illusions or lunar phenomena; find examples in the 18th to the early 19th centuries in Hayakawa et al. (2021). In addition, Secchi's measurements revealed that the radiation emerging close to the limb was roughly half that at the Sun's disk center and let him confirm the presence of the solar atmosphere. By using a thermoelectric pile he also evidenced that sunspots are cooler than other regions of the solar disk.

It is worth noting that Secchi used excellent instrumentation for his solar observations (Altamore & Maffeo 2012). In particular, he used:

Cauchoix telescope: A chromatic refractor telescope with 16.9 cm diameter aperture and 238 cm focal length. This telescope, characterized by an exceptional optical quality (Altamore et al. 2018), was manufactured in 1825 by Robert-Aglae Cauchoix (Paris, France) for installation on an azimuthal mount, but later adapted by Secchi to an equatorial mount for visual observations of the solar disk. This telescope, which was also used for early solar photography and stellar spectroscopy, was equipped with 16 eyepieces having magnification from 40–1500.

Merz telescope: Equatorial refractor telescope with 24.4 cm aperture and 433 cm focal length. This telescope, which was manufactured in 1854 by Merz (Munich, Germany) was one of the best telescopes in the astronomical observatories of the time and one of the largest in Italy (Altamore et al. 2017). Installed in October 1854, it remained in use at the Collegio Romano until 1889 (Tacchini 1901).

Three-prism spectroscope. With a combination of two prisms made by Jean Georges Hofmann (Paris, France) and one prism made by Merz (Munich, Germany), which was used by Secchi to observe the solar limb (Secchi 1872).

Grating spectroscope: Dispersing the light through a diffraction grating instead of a prism train. Two diffraction gratings, one in metal and the other in glass, containing 4000 lines per inch, were made and donated by Lewis M. Rutherfurd in 1874 to Secchi. These allowed excellent observations of prominences (Secchi 1875).

Five-prism spectroscope. Improved by Secchi and described in his treatise on the Sun (Secchi 1875).

As mentioned above, Secchi was well acquainted with scientists of his time. Throughout his life, he was in contact with colleagues in Italy and abroad, mostly in Europe, in order to share knowledge and compare results from simultaneous observations. Besides, he contributed to set methodologies for coordinated solar observations. In collaboration with Pietro Tacchini, an astronomer in Palermo, Secchi contributed to establishing the Societá degli Spettroscopisti Italiani, a society of scientists interested in spectroscopy and its applications for the study of the solar photosphere and chromosphere (Chinnici 2008). The society started in 1872 with the publication of periodic reports in a new scientific journal called *Memorie della Societá degli Spettroscopisti Italiani*. These reports have significant historical and scientific value, as they record data on sunspots, faculae, and prominences over several decades (Riccò 1912). They also form one of the most important collections of solar observations of the time.

Following Secchi's death, the Italian government confiscated the Observatory of Collegio Romano and in 1879 May appointed Pietro Tacchini as its director. The monitoring of the solar atmosphere was continued there until World War I (Millosevich 1918). However, the instrumentation employed by Secchi and his collaborators was gradually decommissioned. Indeed, in 1886, the Cauchoix telescope was disassembled to use its objective with another mount (Altamore et al. 2018). Then, in 1889, the Merz telescope was replaced by a Steinheil–Cavignato refractor and included in the museum collection of the observatory (Altamore et al. 2017). Unfortunately, after it was moved in 1923 to the new location of the museum at the Rome Observatory, the Merz telescope was destroyed by a ruinous fire in 1958. On the other hand, the objective of the Cauchoix telescope, which remained in use for observations at the Rome Observatory until about 1980, has recently been reassembled into the original tube that had been preserved in the museum collection of the Rome Observatory (Chinnici 2020).

3. Secchi's Solar Observations

Secchi made solar observations at the Collegio Romano in Rome (41.9 N, 12.48 E) from 1852 until his death in 1878. From 1858 onward, the observations were performed regularly with the help of Jesuits Paolo Rosa (from 1859–1864), Gaspare Stanislao Ferrari (from 1865 onward; clear examples in 1865, 1867–1869, and over 1872–1873), Nazareno Mancini (over the years 1866–1870), cleric Giuseppe Lais (from 1871 onward), an unidentified observer with the last name of Tosi (1871), and occasionally astronomer Pietro Tacchini during his short visits to the Collegio Romano (1865, 1871, 1873–1874, 1878). Some of them continued the solar observations after Secchi's death, specifically Ferrari and Lais for a few months, and later Tacchini, with new observers, e.g., Elia Millosevich. Note that reading annotations in the observations and of coeval documents allow us to confidently list Secchi's assistants who had contributed to the realization of Secchi's collection of drawings.[9] However, unfortunately, only a few drawings include information for their ultimate attribution to some Secchi's assistants. Attribution of the drawings to potential observers will be the subject of future work after further investigations.

Figure 1. Examples of the cover (left) and spine (right) of one notebook. Information about the location in the INAF OAR archive of the document shown in this figure, as well as of the archival documents shown in the following figures, is given in Section 5 of this paper.

The unique collection of drawings and notebooks that resulted from the solar observations performed by Secchi and his collaborators, under Secchi's supervision, is stored at the INAF OAR historical archive. The material, which is in the form of notebooks, is included in the series *I.1. Osservatorio del Collegio Romano. Attività scientifica*. A total of 14 notebooks of the series contain more than 3900 drawings from solar observations performed regularly from 1858–1878 across different time intervals. In particular, there are five notebooks with drawings covering a full year of observations, two notebooks covering less than a year, and seven notebooks covering a period longer than 1 yr. They are inserted in the subcategory (*sottosottosottoserie*) marked as *I.1.2.1.4.2*. Disegni in the above archival fund. At the time of writing of this article, the fund can be accessed by request to the INAF OAR Director following standard rules to access historical archives.

The drawings in these notebooks were performed in gray pencil on separate sheets of paper of $\approx 29 \times 30$ cm size, by filling most of the sheets. The ones made between 1858 December and 1873 are collated and stitched together in hardbound books with rigid covers, while the drawings dating after 1874 are stored in unbound folders. The appearance of the notebooks and some stamps therein suggest that the binding of loose sheets was presumably coeval.

Figure 1 shows an example of the covers and spines of the above notebooks, which have a consistent format and are well preserved. However, note that the manufacturer of paper sheets employed for the drawings varied over the years, resulting in sheets with slightly different colors, sizes, and textures. Due to small differences in size and coarse stitching of drawings, the pages in the notebooks are thus irregular. Besides, they appear yellowish and sometimes stained by ink or other material. Moreover, the texture of the sheets employed in 1863 includes

[9] See the top left panel of Figure 8 for an example of such annotations.

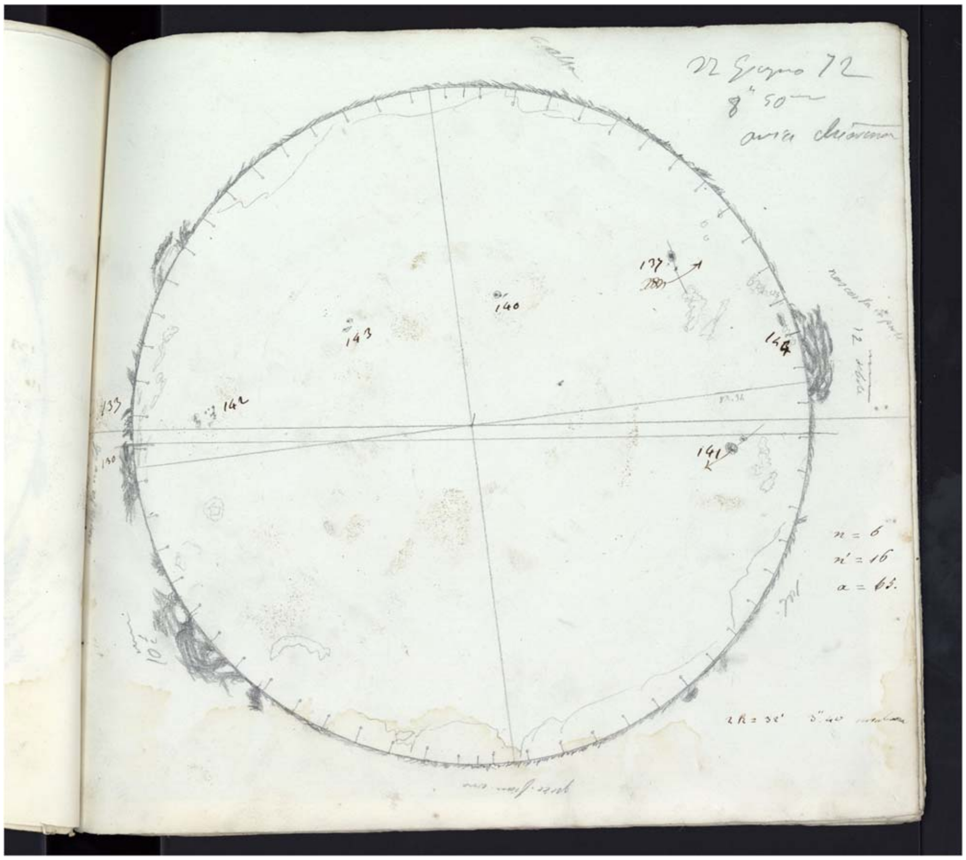

Figure 2. Example of notebook's page with the solar drawing made on 1872 June 22 at 8:50 local time. It shows the sunspots, pores, and faculae observed on the solar surface, as well as the chromospheric spicules and prominences seen at the solar limb. In addition to the observed solar features, there are annotations reporting the date and weather during the observation, identification labels attributed to the observed features, Secchi's counts of sunspots ($n' = 16$), group number ($n = 6$), and sunspot area ($a = 65$ in units of square millimeters), as well as reference lines that allow defining the solar disk orientation and position of solar features. The solar disk in the drawing has a diameter of about 24.3 cm.

a circular trademark of the manufacturer. Note that information about the location in the INAF OAR archive of the document shown in Figure 1, as well as of the archival documents shown in the following figures, is given in Section 5 of this paper.

Almost all drawings in these documents report full-disk solar observations with a disk of about 24.3 cm in diameter. However, there are also drawings with other properties as further described in the following. Note that Secchi and collaborators made the solar drawings on sheets that they had placed on a plate near the eyepiece of the telescope. Therefore, they reproduce the image of the solar disk projected by the telescope. Besides, it is to be noted that each notebook page that includes a solar drawing also contains annotations. These concern the date and time of the observation, and quite often information on weather conditions and the duration of the observation. Moreover, there are annotations with comments on the observed features, as well as the calculation of sunspots' positions, areas, and numbers. Furthermore, various drawings include annotations with information about the number and characteristics of sunspots (sometimes also faculae) on days for which a full-disk drawing does not exist.

Figure 2 shows one example of the pages in the notebooks. The solar drawing therein reports the results of the observation performed on 1872 June 22, and specifically, the sunspots, pores, and faculae observed on the solar surface, as well as the chromospheric spicules and prominences seen at the solar limb. Here, it is worth mentioning that the content of the drawings changed over the period covered by the collection, following the advancement of Secchi's knowledge and instrumentation, as well as practice with solar observations; for instance, until 1863 Secchi had no spectroscopes. In particular, early observations record properties of photospheric sunspots and pores, while drawings in 1861–1866 also show facular and granular regions, the former observed over the disk as well as close to the Sun's poles. On the other hand, the drawings made from 1871–1878 show the photospheric disk features together with the chromospheric prominences and spicules seen at the solar limb. Secchi performed the latter observations by using the Merz telescope in combination with the spectroscope, placing the spectroscope slit tangent to the edge of the solar disk image and then moving it parallel and along the solar rim to explore the low chromosphere. However, he also used it to observe the prominences by aligning the slit perpendicularly to the solar edge.

In addition to the full-disk observations, the above 14 notebooks also include some special drawings. Figure 3 displays two examples of these reproducing sketches of solar features observed in detail and at higher magnification with a change of the eyepiece. The collection contains drawings with enlarged visions incorporated within the full-disk observation, as well as stand-alone representations of the enlarged region. In particular, there are 103 drawings that just include a detailed representation of an active region (without the full-disk drawing), while 121 drawings incorporated details of active

Figure 3. Examples of drawings with detailed and enlarged views of sunspot groups made on 1859 August 28 (top) and 1865 February 16 (bottom). The first one is inside the full-disk drawing for that day, while the second one is a stand-alone sketch. The region of interest in the top image is the one that gave rise to the Carrington event of 1859 September 1. The same drawing is also shown in Hayakawa et al. (2019).

regions within the drawing of the full solar disk for that day. Besides, there are two full-disk drawings that have small paper strips added to their lower part, where there are reproduced the position, shape, and size of the prominences and small-scale jets observed at the solar limb. Figure 4 shows an example of these paper strips, for the observation made on 1871 July 23.

Furthermore, most drawings in the collection report daily observations, but there are a few cases showing the evolution of various solar features observed over several days. This was done either for enlargements of sunspots (see, e.g., Figure 5, bottom panel, reporting the evolution of a sunspot group observed from 1869 April 11–13) or full-disk summary drawings, the latter retaining the position of the spots over the studied period (see, e.g., Figure 5, top panel, documenting the evolution of sunspot groups observed from 1865 October 5–8). Several drawings include raw outlines of faculae seen over the disk, around sunspots as well as isolated (see, e.g., Figure 6), and there are 11 cases with a series of prominence drawings observed at different times within a day. Additionally, the collection includes three drawings documenting the observations of the solar eclipses that occurred on 1860 July 18, 1867 March 6, and 1874 October 11, as well as one drawing reporting the transit of Mercury over the solar disk observed on 1868 November 5. Figure 7 shows two examples of these drawings, lacking information on the solar features observed on those days.

The drawings often, but unfortunately not always, also include an indication of the solar equator and poles. Besides, there are other orientation lines often drawn, reporting, e.g., the vertical reference, the diurnal motion, the ecliptic, a line parallel to the celestial equator, and angular positions at the limb. Although these reference lines often show erasures and corrections, they allow us to define the orientation of the solar disk and the position of solar disk features recorded in the drawings. However, sometimes the reference lines overlap the observed solar features complicating their identification.

Figures 2–7 make evident that Secchi's full-disk drawings were usually schematic and aimed to capture the overall main properties of the observed solar phenomenon rather than its details. Moreover, Secchi was not as talented in drawing as he was in observing and often turned to his assistants to produce detailed sketches of the observed features (Chinnici 2019). Consequently, it is not surprising that his drawings of sunspots are quite raw with respect to sunspot drawings made by his collaborators and by other observers of the time. In particular, several drawings made in 1865 July–August and December, in 1869–1871, and from 1875 onward differ from those performed until that time and most likely are ascribable to his collaborators. As an example, Figure 8 shows two drawings recording the observations performed by Secchi and his collaborator Lais on 1871 May 9. The same set of sunspots and pores observed on that day were reported in the two drawings with clearly different styles and levels of detail. However, Secchi was so attentive to the evolution of the observed features and to the measured data that we can expect no major inconsistencies in the results of his observations. For example, there are annotations on the drawings that link features observed on a given day to solar structures observed in previous or later days, and at different positions on the solar disk. In another instance, an annotation in the drawing made on 1871 May 1 praises the precision of the drawings by Lais and Tosi, but also specifies that those by Secchi, although less precise, contain all the significant data.

In addition to the notebooks with the solar drawings presented above, the Secchi collection also includes five hardbound volumes marked as *I.2.1.4.3. Riduzioni delle osservazioni del Sole* in the archival inventory. The material is in the form of handwritten notebooks with measurements of several properties of the solar features observed from 1871–1878, except for the years 1873–1874, and the calculation of quantities related to them. The data are often also reported in summary tables in separate registers included in these volumes. These archival documents have different sizes and content with respect to each other and the documents

Figure 4. Example of a prominence drawing made on 1871 July 23.

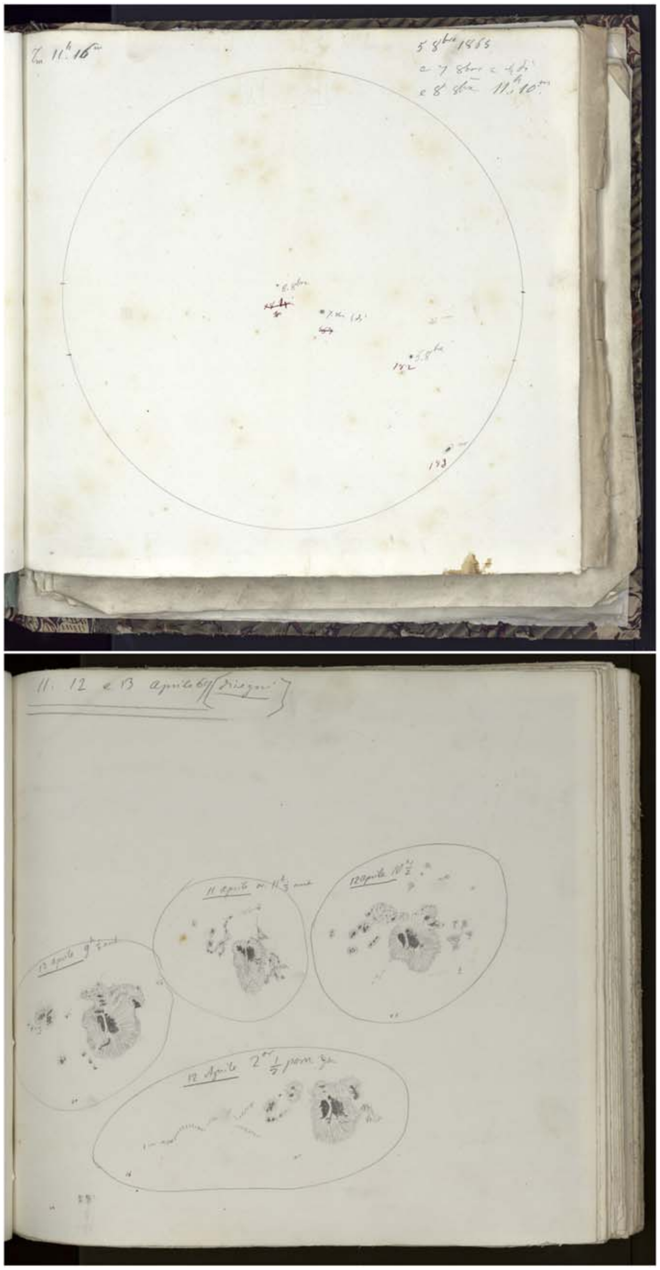

Figure 5. Examples of drawings reporting the evolution of sunspot groups from 1865 October 5–8 (top) and from 1869 April 11–13 (bottom).

presented above. The data in the notebooks mostly record results from the reduction by Secchi and his collaborators of the solar drawings and research notes covering 1 yr of observations. The data relate to the number of sunspots, pores, and sunspot groups, SA and umbra, location, and size of sunspots observed at the solar surface, as well as data of faculae seen on the disk and of prominences observed at the solar limb,

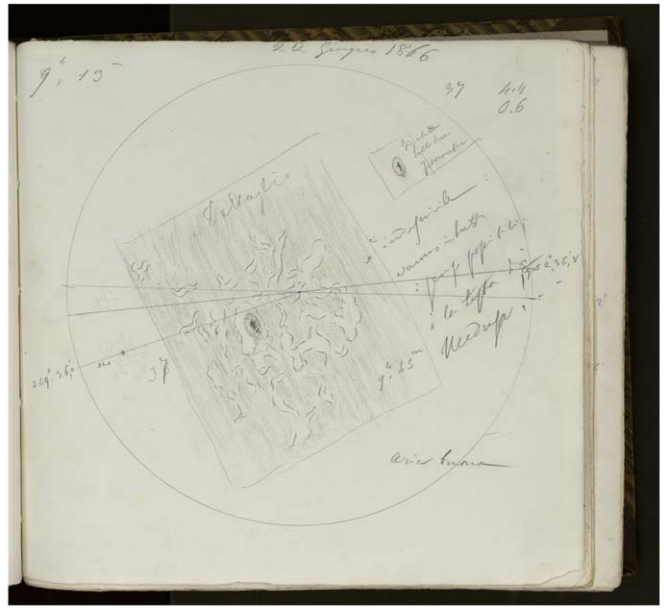

Figure 6. Drawing made on 1866 June 22 that shows an enlargement of a sunspot group clearly outlining the facular regions in the group's surroundings.

with information on their hemispheric distribution. Calculations also refer to the rotation period. Another archival document focuses on measurements of the solar diameter inventoried as *I.1.2.1.4.4. Osservazioni cronografiche del diametro solare*. The content of the notebooks with tabulated data will be investigated more accurately in future work.

Figure 9 shows an example of pages in the registers of the collection, reporting the number and area of sunspots and pores observed in early 1871. It is worth noting that most if not all of the information in this archival material presumably entered Secchi's articles, which appeared in the scientific journals of the time. Indeed, results from the solar observations performed by Secchi and his collaborators are published in several scientific journals, especially the *Bullettino metereologico del Collegio Romano* and the *Memorie della Societá degli Spettroscopisti Italiani*, mentioned previously. However, similarly to the solar drawings, the data in the original notebooks of the Secchi collection have largely been inaccessible so far. In this respect, it is worth mentioning that Carrasco et al. (2021) recently presented a machine-readable version of sunspot and prominence data published in the *Le Soleil* monography along with results from their preliminary analysis of those previously unexplored data. Note that the SAO/NASA Astrophysics Data System (ADS)[10] digital library portal for researchers in astronomy and physics includes 231 entries as per Angelo Secchi. More than half of these entries concern solar physics and heliophysics.

[10] https://ui.adsabs.harvard.edu/

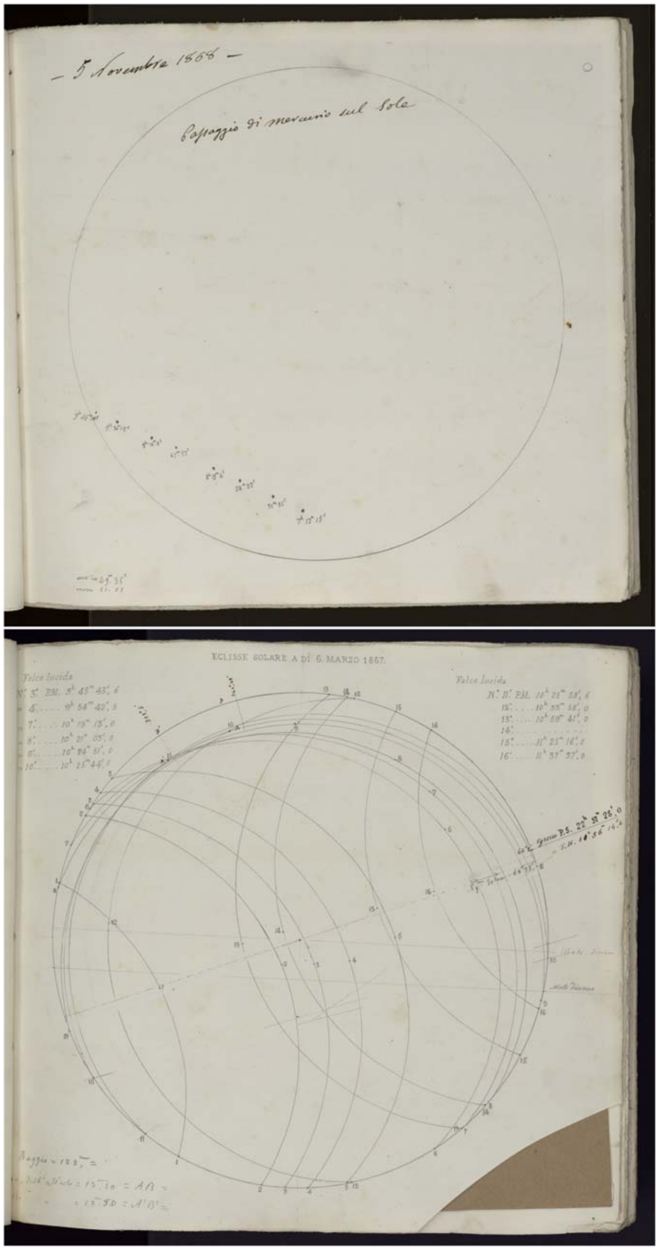

Figure 7. Drawings reporting the observation of the transit of Mercury over the solar disk on 1868 November 5 (top) and of the solar eclipse that occurred on 1867 March 6 (bottom).

Finally, the Secchi collection also contains six small handwritten notebooks that include scattered annotations and sparse data from observations performed prior to 1858 and with the Cauchoix telescope. These documents, which differ from the other notebooks in the collection for their smaller size and different content, are inventoried as *I.1.2.1.4.1. Osservazioni macchie solari al Cauchoix*. Some of these documents include many empty pages, while annotations in some others suggest that they were employed by various observers over different years. It is worth noting that these notebooks mainly record results from observations of stars, comets, and planets. Nevertheless, they also include 13 full-disk solar drawings and 15 close-up drawings of sunspots from observations performed in a few days during the years 1853, 1857, and 1858. Figure 10 shows two examples of these drawings, reporting the observations performed on 1857 May 17 (left panel) and 1858 January 11 (right panel). The drawings were performed in gray pencil, some of them on separate sheets of squared paper later added to the notebooks, others directly on the pages of the notebooks. Note that they differ from the full-disk drawings described above, being significantly smaller and more sketchy than the drawings made after 1858 December. Indeed, the solar disk in these drawings has a diameter of only about 9 cm and sometimes it is also not fully circular. Note that an annotation by Secchi in these drawings lets us know that they were obtained with the finder (Figure 10, left panel).

Figure 11 summarizes information over the period 1850–1878 about the various instruments employed by Secchi (yellow boxes) for his solar observations, the solar features reported in the drawings (green boxes), and Secchi's assistants (blue boxes), some of which just occasional during short visits, as, e.g., Tacchini. Note that Secchi was a great experimenter of instrumental techniques and used different methods during the same observing day, as testified by, e.g., the drawings of enlarged regions of the solar disk overplotted to the results of the full-disk observations, and of the evolution of the observed features. Nevertheless, archival documents attest that Secchi started to use the Cauchoix telescope and prism spectroscopes for solar observations in 1853 and 1863, respectively, and that he had been equipped with the Merz telescope since 1854.

Figure 12 provides summary information on the number of drawings and other data available per year in the Secchi collection. In particular, we show the total number of drawings (green line), the number of drawings of enlarged regions (light blue line), the number of drawings with enlarged regions within a full-disk image (red line), as well as the number of days per year (annual coverage) with group counts from either full-disk drawings or annotations (black line), and from annotations only (yellow line). We further discuss these data in Section 4.

3.1. Digitization of the Collection

Most of the documents in the Secchi collection have been digitized for preservation and diffusion of knowledge under the framework of INAF-funded activities for the valorization of its artistic and documentary heritage. The work was performed by an Italian company specializing in the digitization of manuscripts and historical books. The methods applied entail that all pages in the books of the collection and their back when annotated were digitized, as well as notebooks' front and back covers and spines, to preserve their visual aspects to the fullest. This implies that, e.g., the digital image of a solar drawing often includes a small portion of the subsequent drawing in the notebook and of the previous sheet, i.e., the solar drawing is smaller than the digitized image and framed by something else. Besides, since each hardbound notebook collects many paper sheets, in spite of the careful positioning and flattening of the original document for digitization, sometimes the produced images suffer from small projection effects, especially toward the binding side of the notebook. Furthermore, sometimes the sheet employed for the drawings is so thin that the content of the next page in the notebook is visible through the sheet. This implies that the next solar drawing in the book appears as a faint image on the page under consideration. Note that to avoid this problem the digitization of each page was performed after inserting a thick sheet of paper under the processed page, and in this way, the contents of the following pages were hidden. We note, however, that this was applied only for the drawings

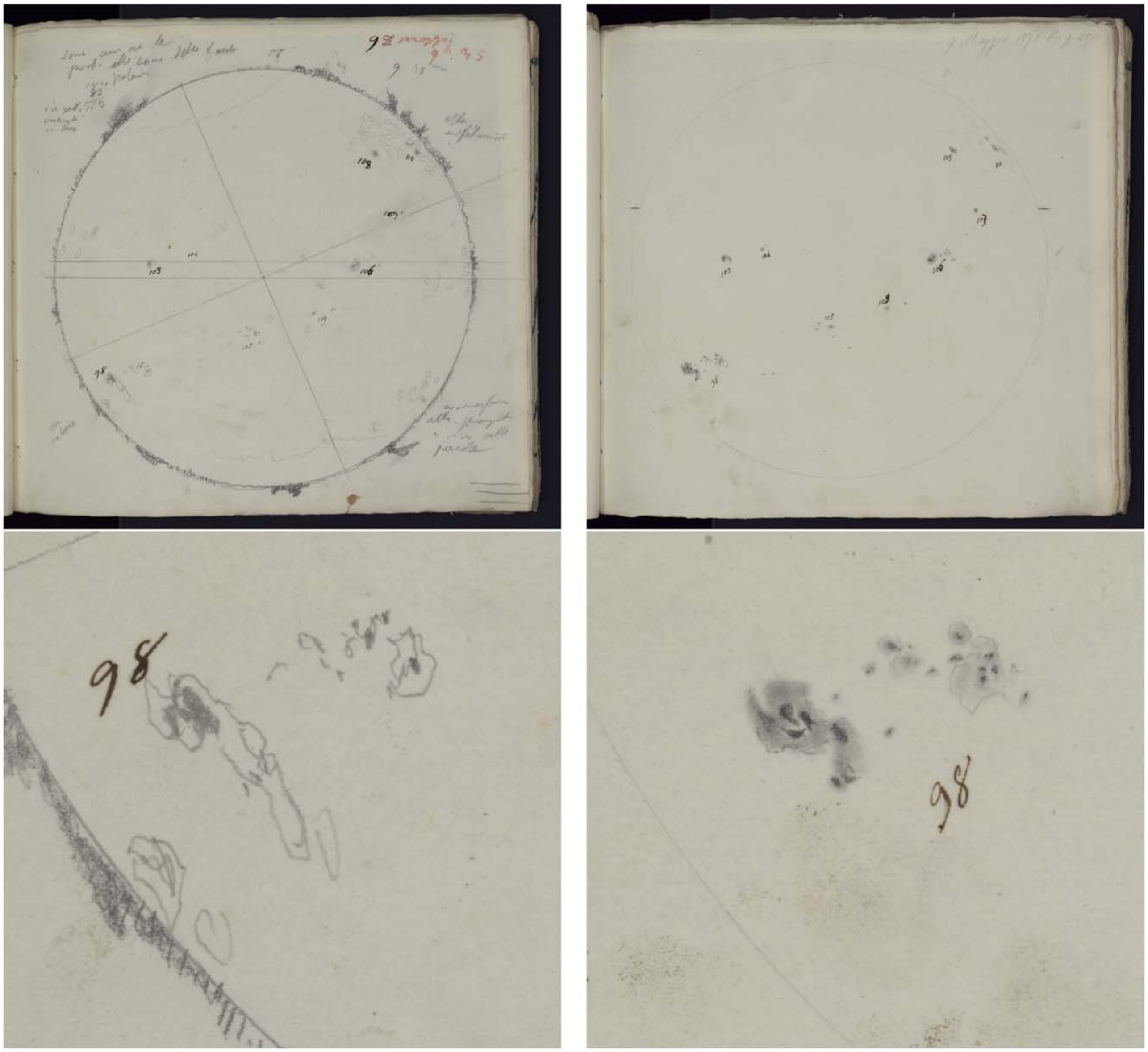

Figure 8. Examples of drawings made by Secchi (left) and his close collaborator Lais (right) on 1871 May 9. The top panels show the full-disk drawing made by the two observers. The lower panels show enlarged areas around group #98 to highlight the different techniques in drawing sunspots by the two observers.

since 1861 July 27. While avoiding ghosts of solar observations and annotations, the employed method has however slightly modified the appearance of the digitized page and decreased the intensity range therein. However, that still could not help with possible annotations or drawings on the back side of the paper sheet. Indeed, we note that the back sides of the sheets with full-disk drawings sometimes include further annotations.

The digitization of the archival documents was performed at the INAF OAR with a SUPRASCAN DIGBOOK 10000 RGB scanner. This device was equipped with a color camera, motorized and controlled remotely, to allow the acquisition of 42 bit (3 × 14 bit) red, green, and blue images.

The notebooks were placed on the digitization plate, which was either flat or foldable depending on the size and weight of the book. The digitized documents were illuminated by using an LED cold light.

Reference standards were acquired daily by using the Golden Thread Target manufactured by Image Science Associates and the Kodak Q-14, CAT 1527662 system to check the setting of the scan and ex post facto control of the illumination and scale of the digitized data.

After the application of standard instrumental compensations, each digitized page or element of the notebooks was returned as a TIFF 400 dots per inch (dpi) image of about 5000 × 5000 pixels and about 80 MB. For easy access and a quick look, the same images were also stored as compressed JPEG 300 dpi and JPEG 150 dpi files of variable sizes ranging from 0.3–6 MB.

The filenames of the digital data include metadata, namely, information on the corresponding location in the INAF library of the archival document and of the date and time of the observation, as they were recorded in the solar drawing. Images derived from the digitization of the notebooks' front cover and other details, and documents lacking the date of observation are stored with the filename format describing only the archival corresponding location.

The processing steps applied to the digital data do not include rotation to compensate for small misalignment of the document with respect to the digitization floor.

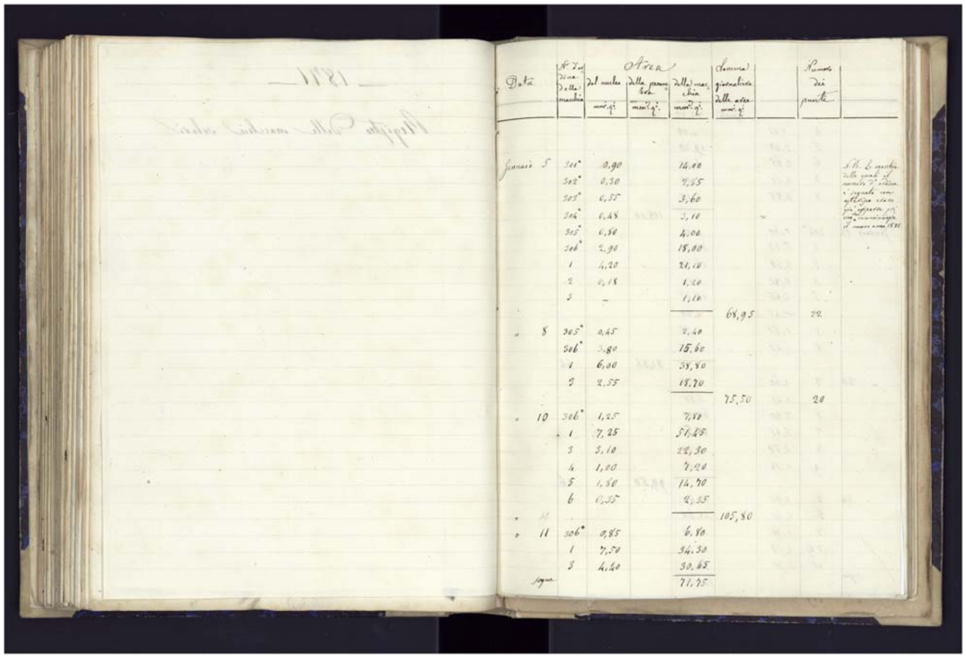

Figure 9. Example of pages in the handwritten notebooks with measurements of properties of the observed solar features and calculation of quantities related to them. This example refers to pores and sunspot data recorded in early 1871. The tabulated values refer to the date of the observation (January 5, 8, 10, 11; column 1); identification number of the observed sunspot (column 2); SA (umbral, penumbral, and total area given in square millimeters; columns 3–5); total SA daily value (column 6); number of observed pores (column 7); annotations (column 8).

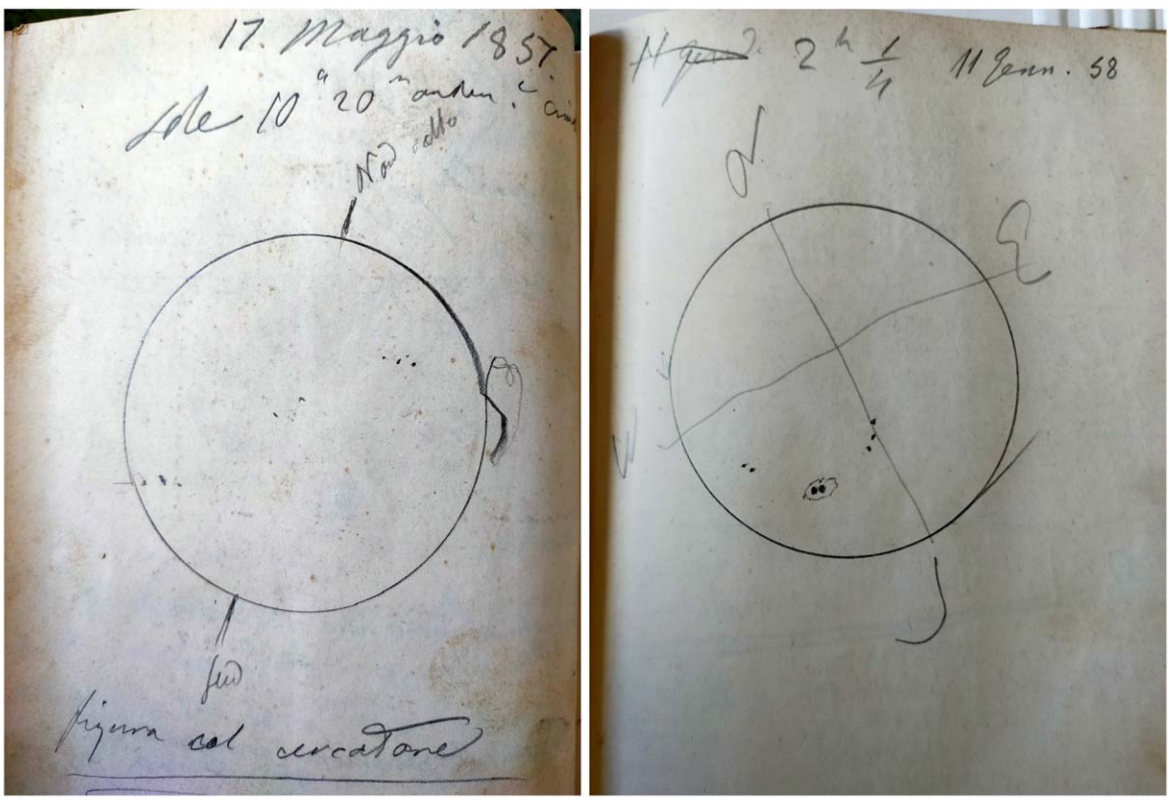

Figure 10. Examples of drawings made prior to 1858 December, reporting the results of the solar observation performed on 1857 May 17 (left) and 1858 January 11 (right).

Note that all the documents described in the previous section were digitized with the methods and setting described above, except for the six small notebooks, which include sparse data from observations of various types, due to their different format and constraints on the digitization work. However, the few solar drawings included in those notebooks were photographed with a digital Nikon camera and natural light, producing images of about 6000×4000 pixels stored as compressed JPEG 300 dpi files for the analysis described in the following.

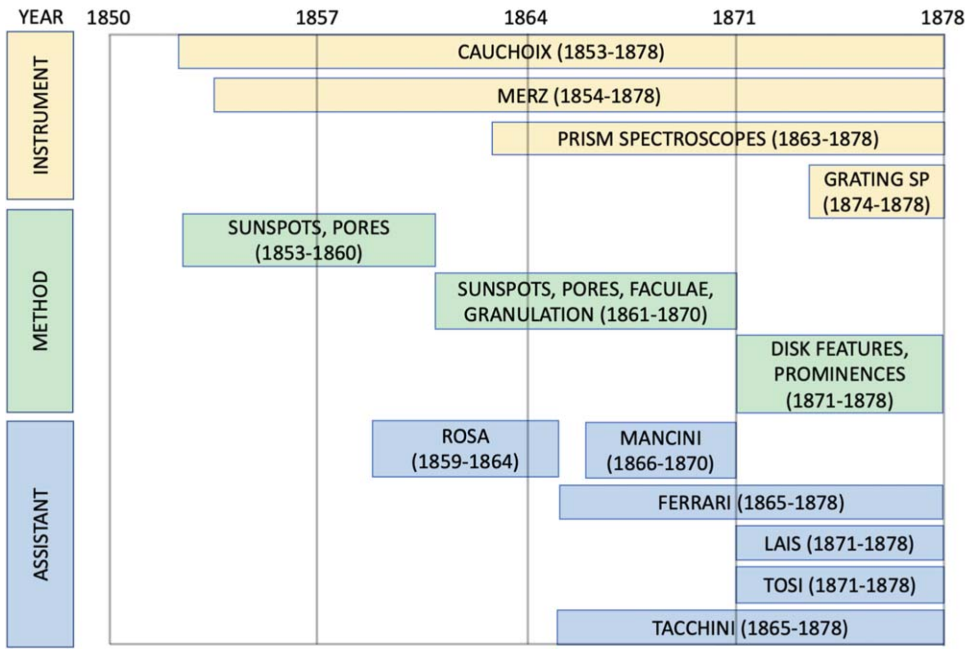

Figure 11. Infographic summarizing information about the instruments employed by Secchi (yellow boxes), the solar features reported in the drawings (green boxes), and Secchi's assistants (blue boxes) over the period of 1850–1878. Find more details in Section 3.

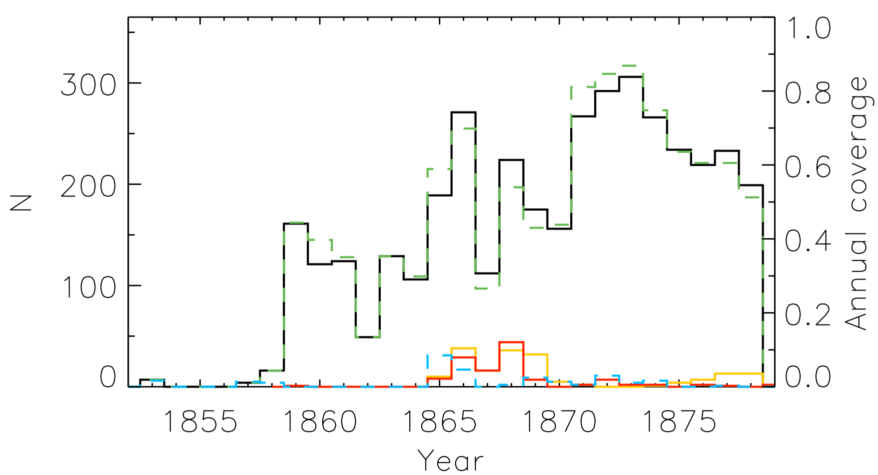

Figure 12. Number of solar full-disk observations per year in the collection. Number of days per year with group counts (either from full-disk drawings or annotations; black), number of days per year with information on group counts in annotations (yellow), total number of drawings (dashed green), number of drawings of enlarged regions (dashed light blue), and number of images that included enlarged regions within a full-disk drawing (red). The days with information on group counts are also expressed as the fraction of days within a year as shown in the right *y*-axis.

4. Analysis of the Digital Data

It is worth noting that Secchi did mark sunspot groups in many drawings of the collection, while summary tables of various properties of sunspot groups, faculae, and prominences were also compiled as part of the collection. However, this information only exists for a few years in tabulated form. Besides, many drawings did not include any delineation among the groups. Furthermore, the grouping conventions have changed over time after Secchi's observations. Due to these reasons, a full and accurate recounting of sunspot groups on the available drawings based on modern morphological sunspot group classification (McIntosh 1990) is essential in order to exploit all the information about sunspot groups included in the Secchi collection. In the following sections, we describe our work to recount sunspot groups from the solar drawings made from 1853–1878. Note that the drawings analyzed in our study are those made by Secchi and his collaborators, under his supervision, until Secchi's death in 1878 February, and those collected by Secchi's collaborators until the end of 1878, i.e., slightly before Tacchini was appointed as the new director of the Collegio Romano Observatory.

4.1. Methods

We have developed a set of codes to derive accurate group counts from the new digital data. In particular, for our analysis, we first converted the images obtained from the digitization work to Flexible Image Transport System (FITS; Wells et al. 1981) file format. On these images, we identified the solar limb as an ellipse, following Chatzistergos et al. (2020a, 2020b) to account for potential distortions introduced during the digitization of the drawing. The information on the semimajor and -minor axes, along with the ellipse angle were stored in the

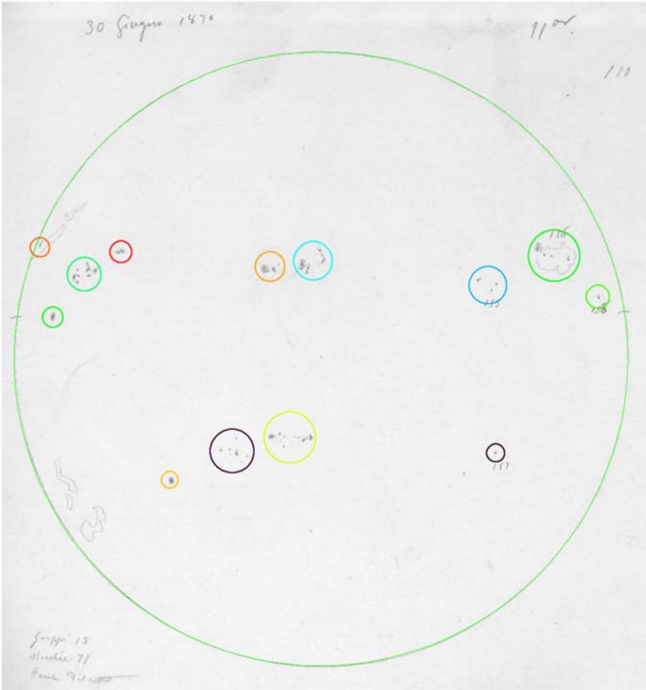

Figure 13. Example of a mask derived by recounting sunspot groups in Secchi's drawing of 1870 June 30. The outermost green circle marks the solar disk, while each group is marked with a colored circle.

FITS file header. Then we identified the sunspot groups on the images manually with a routine that allowed the user to select the groups with two mouse clicks in the image per group, the first click providing information on the approximate center of the group and the second one on the radius of the group. For each group we maintained this information, allowing us to produce masks of the available groups on the solar disk. The results derived from the group identification were tested and verified through independent measurements of subsets of the data made by four authors of this study. We show in Figure 13 an example of the masks derived from the image processing. Note that the produced mask only includes the part of the analyzed image with information relevant to group identification.

It is worth mentioning that a semiautomatic processing of the new digital data was also tested. The algorithm developed for this purpose made use of the information on the solar disk and identified dark regions based on an intensity threshold, which was set relative to the empty part of the drawing. Morphological operators were applied to expand the regions and close potential open loops. Supervision was needed at this point to ascertain that the groups were correctly selected. Unfortunately, the variations of the drawings over time as well as the various markings therein rendered the performance of this approach to be highly variable and requiring extensive supervision. In particular, the developed algorithm resulted in working satisfactorily only on the drawings lacking reference lines, enlargement of the drawings of the active region, and inscriptions within the solar disk, which represent a minority of the analyzed data. Therefore the tested approach was used only for a small sample of the drawings and for preliminary analyses. Note that the data presented in the following derive from a consistent manual identification of sunspot groups on all the available drawings. We also noticed that for our analysis we used the majority of the available drawings, but we had to ignore some of them. The drawings left out from our study comprise close-ups of sunspots, drawings that did not include information on sunspots (e.g., Mercury's passage or eclipse observations), but also drawings with annotations reporting poor weather conditions and incomplete sunspot information (e.g., drawings made on 1870 May 21 and 25). Nevertheless, in order to provide a group number series from Secchi's observations as complete as possible we also incorporated various information on sunspot groups from annotations on the sides of solar drawings. Such annotations provide information for the group counts for days for which there is no full-disk drawing of the Sun. The majority of these annotations refer to spotless days for which the observer deemed unnecessary to make an empty drawing. However, we note that plenty of empty drawings signifying spotless days also exist in the Secchi collection. In particular, there are 128 spotless days mentioned in the notebooks without a drawing. Besides, there are eight drawings of close-ups of sunspot groups for which the annotations imply that they are the only groups visible on the solar disk, and thus can still be used to count groups. Furthermore, there are 41 days for which there are comments that either there was nothing new on the disk or explicitly mentioning the disappearance of specific groups. For these cases we used our counting of the referred date, however, we checked whether the appearance of the groups on the described period would be feasible when taking into account the solar differential rotation. There were seven cases for which we found groups that due to differential rotation should not be visible on the corresponding dates from the annotations. For instance, on the drawing made on 1868 August 2, it is mentioned that the two groups observed on that day were also visible in the following days, and specifically from August 3–6. However, we noticed that, due to the proximity of one group to the limb, it should have disappeared after August 4. The annotation in the drawing may thus imply that a new group had appeared on the disk together with the disappearance of the one close to the limb, but due to the lack of any evidence of the former, this remains rather speculative. To be on the safe side, we decided to ignore such ambiguous cases from our group counts. For completeness, we list all of these cases as a separate group in the Excel table summarizing information on annotations relevant to our study that is made available in the data.tar.gz package.

4.2. Sunspot Group Numbers

Figure 14 shows the daily (black circles) and annual (red solid line) series of the group numbers from our analysis of the drawings in the Secchi collection, which record results from solar observations performed from 1853 to 1878. This period includes the descending phase of solar cycle (SC) 9, and the entire SC 10 and SC 11. Also shown in Figure 14 are the annual mean values of S_N (dashed light blue) and the group number series by Chatzistergos et al. (2017). We chose to show the group number series by Chatzistergos (2017) because it has daily values and is favored by various tests (Clette et al. 2023). We did not consider the other group number series with daily values, the one by Hoyt & Schatten (1998), because of the various criticisms of its cross-calibration approach (Lockwood et al. 2016; Usoskin et al. 2016; Clette et al. 2023), as well as its reliance on outdated sunspot data, which have undergone numerous corrections and revisions since then (Vaquero et al.

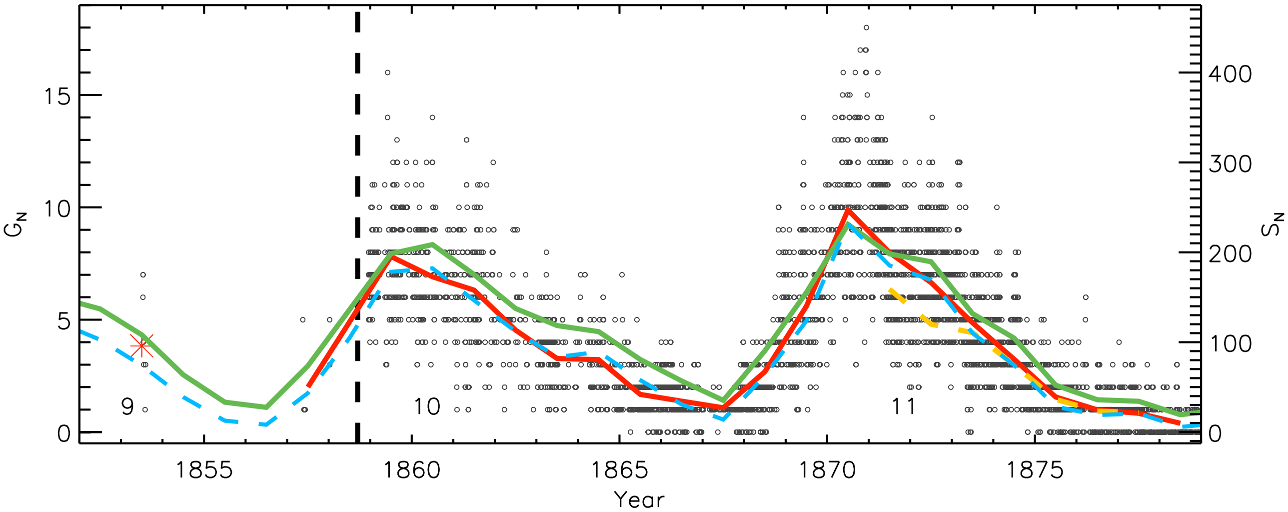

Figure 14. Group numbers derived from the drawings of the Secchi collection in this study (daily counts are shown in gray and annual mean values in red). Also shown are the annual values of the group number series by Chatzistergos et al. (2017, solid green) and S_N (the values are given in the right axis; dashed light blue) as well as the raw group counts of Secchi (dashed yellow) from the Vaquero et al. (2016) database. The vertical dashed black line separates the sporadic data prior to 1858 December and the regular ones afterward. The numbers at the lower part of the figure denote the conventional solar cycle numbering.

Table 2
Annual Mean of the Group Numbers Derived from This Study and Number of Days ($N_{\rm days}$), Number of Drawings ($N_{\rm draw}$), and Number of Annotations ($N_{\rm anno}$) Analyzed per Year

Year	G_N	$N_{\rm days}$	$N_{\rm draw}$	$N_{\rm anno}$
1853	3.8	7	7	0
1857	2.0	4	4	0
1858	4.9	16	16	0
1859	7.8	161	162	0
1860	6.9	121	127	0
1861	6.3	124	128	0
1862	4.5	49	49	0
1863	3.3	129	129	0
1864	3.2	106	109	0
1865	1.7	189	194	10
1866	1.4	271	275	38
1867	1.1	112	112	16
1868	2.7	224	230	36
1869	5.6	175	178	32
1870	9.8	156	158	5
1871	8.0	267	293	2
1872	6.7	292	298	0
1873	4.9	306	314	0
1874	3.2	266	268	1
1875	1.6	234	236	4
1876	1.0	219	220	7
1877	0.8	233	233	13
1878	0.4	199	200	13

2016). According to the SILSO database, the minimum (maximum) of SC 10 and SC 11 were on 1855 December (1860 February) and 1867 March (1870 August), respectively. We find our group numbers from Secchi's drawings to follow very closely the variations in the S_N over cycles 10 and 11. On the other hand, compared to the group number series by Chatzistergos et al. (2017) we find our group numbers from Secchi's drawings to be consistently lower at all times except the maximum of SC 11.

Table 2 lists the annual mean values of group numbers derived from our analysis of Secchi's drawings. Note that these values were obtained from monthly mean assessments based on the daily values of group numbers derived from our study. The latter are provided in Table 1. We note that there are no drawings in the collection for the years 1854–1856, and that those available for the years 1853, 1857, and 1858 are just a few. This can affect the annual values derived for those years. We also note that the lack of solar drawings for the years 1854–1856 coincides with a period of Secchi's regular observations of astronomical objects other than the Sun. For our study we have checked all the relevant notebooks of that period in the INAF OAR archive, not necessarily referring to solar observations, but we could not locate any more solar drawings. Considering the fact that the few solar drawings we found for the years prior to 1858 were in notebooks with a title referring to the Sun, however, these notebooks comprise mostly observations of other stars, planets, and comets, we suspect that it is very likely that there are no more potentially lost or destroyed solar drawings by Secchi for that period. However, we cannot conclusively exclude the possibility that there might still be more drawings and data from Secchi's solar observations for years prior to 1858 yet to be recovered.

Figure 14 also compares the annual series of the group numbers derived from our study to the annual series of group numbers attributed to Secchi in the literature. Indeed, Secchi's sunspot observations were previously analyzed by Hoyt & Schatten (1998), and the corresponding records were later included in the database of raw group counts compiled by Vaquero et al. (2016).[11] This database also includes records of group numbers from other contemporary scientists of Secchi, such as Johann Rudolf Wolf and Julius Schmidt, as well as from some of Secchi's collaborators and assistants, specifically Pietro Tacchini in Palermo and Gaspare Stanislao Ferrari in Rome.

Figure 14 shows that the values of group numbers derived from our study of Secchi's observations cover a significantly longer period than those previously available in the literature. Besides, for an interval of about 2 yr in the overlapping period of the two series, from 1871–1873, the values from our study

[11] http://haso.unex.es/haso/index.php/on-line-archive/data/

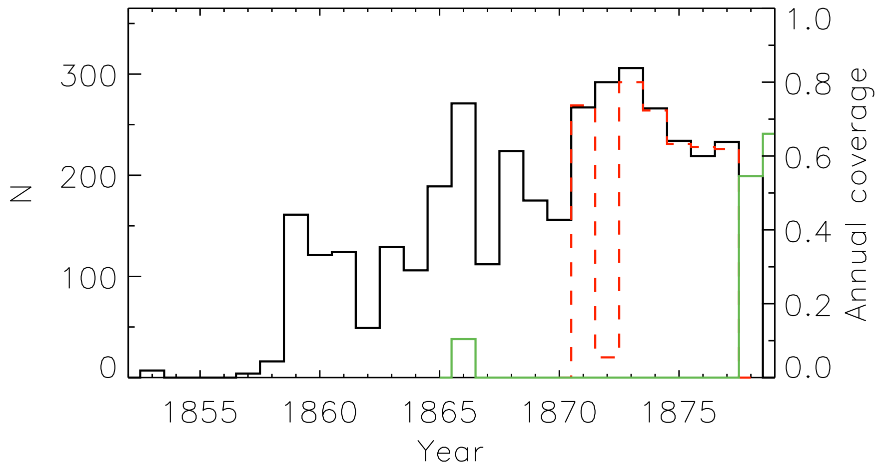

Figure 15. Comparison of the number of days per year with information on group counts in the Secchi collection (black) and those from Secchi (red) and Ferrari (green) in the Vaquero et al. (2016) database.

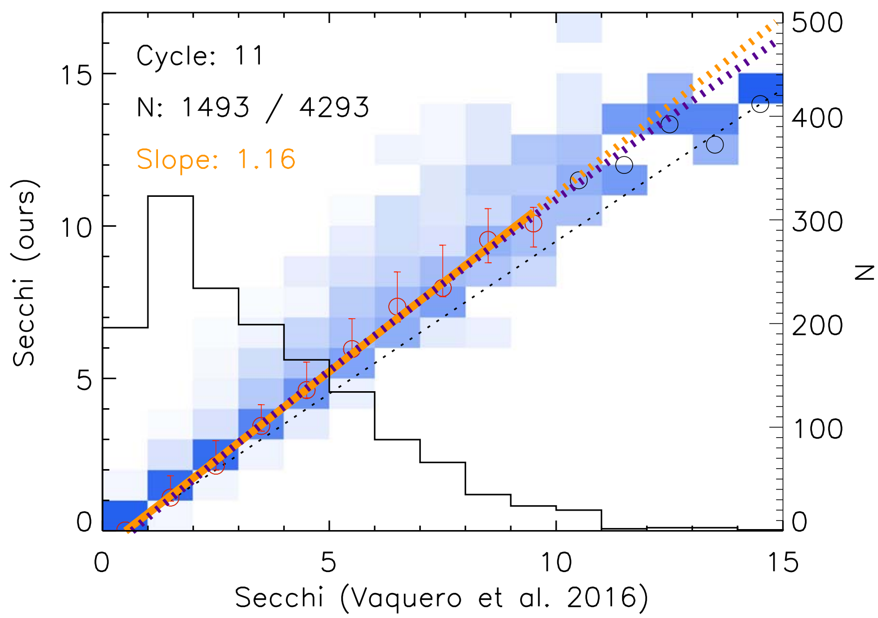

Figure 16. Comparison between group numbers derived from this study and those in the Vaquero et al. (2016) database. Shown are probability distribution matrices following Chatzistergos et al. (2017). The PMF matrices are color coded with dark blue for a probability of 1 and white of 0. For each column, the mean group count is marked with a circle (red when the column has data for more than 20 days and black otherwise) also giving the asymmetric 1σ intervals. The histogram shows the number of days populating each column. The orange and purple curves are linear and exponential fits following Chatzistergos et al. (2017) to the mean values of the distributions. Within the panel, also listed is the the solar cycle for which there is overlap between the counts of the two compared series, as well as the total number of overlapping days vs. the total number of days for the solar cycle along with the slope of the linear fit. The black-dotted line has a slope of unity.

are larger than those reported for Secchi's observations in the Vaquero et al. (2016) database.

We note that our primary analysis of the digitized drawings increases considerably the amount of available group data from Secchi's solar observations. For clarity, we compare in Figure 15 the number of days per year with information on group counts as derived from our analysis of the drawings in the Secchi collection (black) and those from Secchi (red) and Ferrari (green) existing in the database compiled by Vaquero et al. (2016). Figure 15 makes clear that the digitization of the Secchi collection and our primary work on it have remarkably expanded the data available from Secchi's observations. This is particularly important because it allows future cross-calibrations of group numbers to make use of Secchi's data for periods prior to 1871 and for most of 1872, which were missing before.

However, we find 35 days (extra days, hereafter) for which there is a record of observation by Secchi in the database by Vaquero et al. (2016), but we could not find either a drawing or annotation referring to those days. We note that Secchi's data in the database by Vaquero et al. (2016) derive from the data set compiled by Hoyt & Schatten (1998) using measurements published in the literature (Secchi 1859; Wolf 1865, 1873, 1874, 1875, 1876, 1877, 1879), which refer to data in the volumes of the Secchi collection. We have consulted Secchi's documents and found that they actually include data for the extra days. We can therefore hypothesize that the data for those days derive from observations not reported in drawings because of lack of time or other reasons, or from drawings or annotations that were lost or archived elsewhere, or potentially even from other observers. Indeed, we note that all the extra

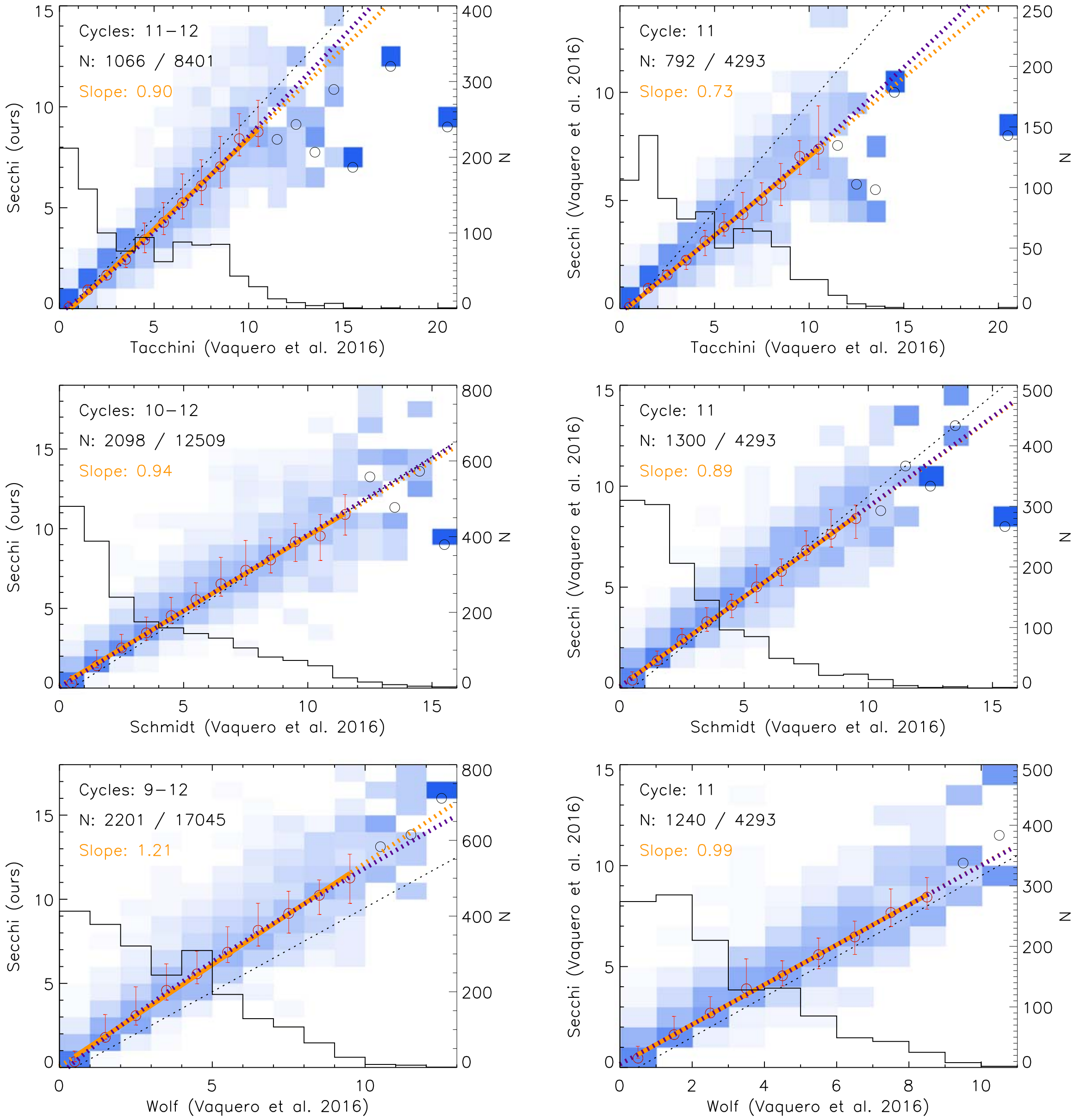

Figure 17. Comparison between group numbers derived from our study and by Secchi and other observers as reported in the database compiled by Vaquero et al. (2016). In particular, we compare the Secchi records as recounted in our study (left column) and the Secchi records in the Vaquero et al. (2016) database (right column) to the data by Tacchini (fist row), Schmidt (second row), and Wolf (third row). Shown are probability distribution matrices following Chatzistergos et al. (2017). See Section 4.2 and the caption of Figure 16 for more details.

days are in the years 1871–1877, i.e., when Secchi and Tacchini were used to share information on their observations. For consistency, we did not add the group counts of the extra days in the Vaquero et al. (2016) database to the results obtained from our study of the drawings because the origin of the former data is other than the drawings and is actually unknown to us at present. Besides, they derive from the application of the group classification adopted by Secchi, which likely differs from the one used in our counts. Planned future work includes digitization and analysis of the tables of measurements compiled in the volumes of the Secchi collection. This will allow us to further investigate the origin and consistency of the data attributed to Secchi in the literature. Finally, we note that the group data over the period analyzed in our study attributed to Ferrari in the database by Vaquero et al. (2016) are limited to the years 1866 and 1878, with very few observations for the year 1866 and data for the year 1878 that seem to coincide in number with the ones analyzed in our study.

Looking more closely into the differences among the diverse data sets, in Figure 16 we show the daily values of group numbers derived from our analysis to those attributed to Secchi in the database compiled by Vaquero et al. (2016). In particular, following Chatzistergos et al. (2017), we show the probability mass function (PMF)[12] matrix for the values from our study as a function of the values in the database used as the reference. Only values in the two series relating to the same days are considered, and sorted in bins of 1 unit. The resulting matrix is color coded with dark blue for a probability of 1 and

[12] Previously referred to as a probability distribution function.

Table 3
Documents of the Secchi Collection in the INAF OAR Archive

Unit	Archive Position	Document
1	B12	Macchie solari al Cauchoix—studi; dall'anno 1853 all'anno 1854
2	B12	Macchie solari. Annotazioni diverse. Anno 1858
3	B12	Registro giornaliero delle macchie solari osservate al Cauchoix con il metodo del padre Ferrari
4	B12	Macchie solari al Cauchoix dal 1 agosto 1865 all'anno 1869
5	B12	Macchie solari. Dal 18 ottobre 1870 al 30 maggio 1871
6	B13	Macchie solari, 16 decembre 1858-30 settembre 1859
7	B13	Macchie solari. 1 ottobre 1859-6 giugno 1861
8	B14	Macchie solari. 8 giugno 1861-29 giugno 1864
9	B14	Macchie solari. 5 luglio 1864-18 decembre 1865
10	B15	Macchie solari. Anno 1866
11	B16	Macchie solari. Anno 1867–1868
12	B17	Macchie solari. Anno 1870–1869
13	B18	Disegni proiezioni delle macchie solari. Anno 1871
14	B19	Disegni proiezioni delle macchie solari. Anno 1872
15	B20	Disegni proiezioni macchie solari. Anno 1873
16	B21	Disegni proiezioni delle macchie solari. Anno 1874–1875
17	B22	Disegni proiezioni delle macchie solari. Anno 1875–1876
18	B23	Disegni proiezioni delle macchie solari. Anno 1876–1877
19	B24	Disegni proiezioni delle macchie solari. Anno 1877–1879
20	B33	Riduzione delle osservazioni del Sole. Anno 1871
21	B33	Riduzione delle osservazioni del Sole. Anno 1875
22	B33	Riduzione delle osservazioni del Sole. Anno 1876
23	B34	Riduzione delle osservazioni del Sole. Anno 1877
24	B34	Riduzione delle osservazioni del Sole. Anno 1878
25	B34	Osservazioni cronografiche del diametro solare
26	B38	Sole. Tavole 1871–1872
27	B43	Osservazioni all'Equatoriale. Dal 23 maggio 1851 al 26 giugno 1851
28	B44	Osservazioni all'Equatoriale. Dal 25 giugno 1860 al 13 maggio 1861

white of 0. For each column, the mean group count is marked with a circle (red for those in which the column has data for more than 20 days and black otherwise) also giving the asymmetric 1σ intervals. The histogram shows the number of days populating each column. The orange and purple curves are linear and exponential fits following Chatzistergos et al. (2017) to the mean values of the distributions. Within the panel, also listed is the the solar cycle for which there is overlap between the counts of the two compared series, specifically SC 11, as well as the total number of overlapping days versus the total number of days for SC 11 along with the slope of the linear fit. It is worth noting that the overlapping days cover only about 33% of SC 11, while our reanalysis of Secchi's data provides group counts for 59% of the days in SC 11 as well as 27% of SC 10. Overall, Figure 16 shows that our recounting of group numbers from Secchi's drawings resulted in slightly larger values compared to those previously reported in the Vaquero et al. (2016) database, as also shown in Figure 16. We note that the values in the compared series differ from smaller to larger counts, hinting at different counting methods applied to derive the values in the two series. We also note that the effect of different counting of Secchi's data appears to be described well with a linear relation, in contrast to the nonlinear effect of different observer acuities due to different telescope magnification reported by Usoskin et al. (2016) and Chatzistergos (2017).

As mentioned above, the reference database also includes data of group numbers attributed to some collaborators of Secchi and scientists of his time. In Figure 17, we compare the records of Tacchini, Schmidt, and Wolf extracted from the reference database to the records from our study of Secchi's drawings and those for Secchi in the database. Here again, we consider daily values of group numbers and PMF matrices for the values from our study as a function of the values in the reference database for the compared series.

Figure 17 shows that our recounting of group numbers from Secchi's drawings resulted in a slightly closer agreement with those reported for Tacchini and Schmidt in the Vaquero et al. (2016) database than obtained by considering the same series and the Secchi data set in the database. However, there is an increased disagreement with Wolf's records. Differences between our group number counts and those referred to Secchi in the Vaquero et al. (2016) database likely depend on different methodologies to define sunspot groups applied in our study and at the time. In addition to the above reason, the diverse values in our counts and those referred to Tacchini and other observers in the reference database likely also depend on the different instruments or weather conditions during their observations (see Usoskin et al. 2016; Clette et al. 2023). Finally, we note that the annotations in the drawings allow us to attribute some of them to four different observers in addition to Secchi. However, the evolution of the drawings and the richness of their details make it difficult to classify the documents depending on the potential author. We defer this task to future work, since it requires knowledge and expertise on handwritten documents not available at the time of this study.

5. Summary and Conclusions

In this study, we have presented the collection of solar drawings and notebooks made by Angelo Secchi, a Jesuit and prominent scientist of the 19th century, from solar observations performed with excellent instrumentation at the Collegio Romano in Rome. The collection, which is stored in the historical archive of the Istituto Nazionale di Astrofisica Osservatorio Astronomico di Roma, includes documents produced by Secchi and a few of his close collaborators and assistants from 1853–1878. Note that, as to the knowledge of the authors, some of the drawings in the collection were reproduced and published, specifically those relevant to the observation of prominences from 1871 onward that were reported in the volumes of, e.g., *Memorie della Società degli Spettroscopisti Italiani*. Besides, data derived from the full-disk observations were published in, e.g., *Le Soleil* and other treatises listed in the bibliography of the present paper, but most of Secchi's solar observations drawings and notebooks just remained archived at the Collegio Romano Observatory. Analysis of close matching between archival material and published documents will be the subject of future work.

Historical solar observations are a direct key to knowing the Sun's past. They provide valuable information about the dynamo, activity, and variability of the Sun (Pevtsov et al. 2019). Over recent years, new science drivers and the

Table 4
Position in the INAF OAR Archive of the Historical Documents Shown in Figures 1–10 and Filename of the Corresponding Digital Images

Figure	Archive Position	Image Filename
1	B13F072	INAFRM_10131_B13F072_0001.jpg
2	B19F080	INAFRM_10139_B19F080_0147_18720622-0850.jpg
3 top	B13F072	INAFRM_10131_B13F072_0147_18590828-1000.jpg
3 bottom	B15F076	INAFRM_10135_B15F076_0042_18660216-1500.jpg
4	B18F079	INAFRM_10138_B18F079_0172.jpg
5 top	B14F075	INAFRM_10134_B14F075_0247_18651005-1116.jpg
5 bottom	B17F078	INAFRM_10137_B17F078_0052_18690411-xxxx.jpg
6	B15F076	INAFRM_10135_B15F076_0145_18660622-0913.jpg
7 top	B16F077	INAFRM_10136_B16F077_0275_18681105-1030.jpg
7 bottom	B16F077	INAFRM_10136_B16F077_0012_18670306-1000.jpg
8 left	B18F079	INAFRM_10138_B18F079_0099_18710509-0945.jpg
8 right	B18F079	INAFRM_10138_B18F079_0077_18710509-0945.jpg
9	B33F094	INAFRM_10154_B33F094_0148_18710105-18710111.jpg
10 left	B43F156	INAFRM_XXXXX_B43F157_XXXX_18570517-1020.jpg
10 right	B43F157	INAFRM_XXXXX_B43F157_XXXX_18580111-0930.jpg

availability of new digitizing and computing resources have favored the digitization of several series of historical solar observations, as are, e.g., collections of drawings and annotations from visual observations made in the pre-photographic period (Arlt & Vaquero 2020), and of a few archives of solar photographic observations (Chatzistergos et al. 2022). Recently, machine-readable versions of data published in historical books have also been produced (Carrasco et al. 2021).

The digitization of historical observations, in addition to providing digital versions of the original archival material, has also allowed the analysis and generation of new measurements of sunspots and other solar disk features observed in the past. Under this framework, the digitization of the collection of drawings and notebooks from the solar observations performed by Angelo Secchi presented in this study is especially important. In fact, it favors the preservation and exploitation of the historical data recorded in those archival documents, which were previously largely inaccessible. Besides, it adds new data to a limited number of catalogs of solar observations in the 19th century (Lefevre & Clette 2014). This will help inter-calibrate the series from individual records of the time and identify inconsistencies contained in previously published series of, e.g., sunspots' properties (Muñoz-Jaramillo & Vaquero 2019).

In this study, we have presented the results derived from our primary analysis of the new data derived from the digitization of Secchi's solar observations. This analysis recounted the number of groups from Secchi's solar drawings over 1853–1878. The new series of group numbers derived from our study extends significantly the previously available records for group data attributed to Secchi in the literature, by increasing the group data available over the 19th century. This has the potential of improving the cross-calibration of records from different sources and thus significantly improving our knowledge of solar activity on long-term timescales. It is worth noting that the results presented in this study only derive from our primary analysis of the new digital data. Priority was given to the derivation of group numbers from the new digital data because those numbers can readily be used for recalibrations of the several existing group sunspot number series that enter many studies and models (see Section 1). That is not the case for other data that could be extracted from Secchi's drawings, such as individual sunspot numbers or characteristics of faculae and prominences. For example, a complete recalibration of a sunspot number series is not possible at the moment because a large part of the historical sunspot data from various observers required for this task is still waiting for digitization and their availability in digital form (Clette et al. 2023). We also note that ongoing work shall soon lead to the derivation of accurate single sunspot number counts and SA values from Secchi's drawings. However, this is a rather difficult task that requires special caution due to the sketchy nature of Secchi's observations and the changes in their content over the years (see Section 3). When derived, these data will be useful for future recalibrations of the new sunspot number series (Clette et al. 2023; Pevtsov et al. 2023). Moreover, future work will also study the chromospheric features reported in Secchi's solar observations, in order to extend back the data available for those features and fully exploit the rich potential of the newly digitized series of drawings and notes of the Secchi collection.

Finally, the archival material presented in this study is available online at Internet Culturale,[13] which is the portal of digital collections of Italian libraries by *Istituto Centrale per il Catalogo Unico delle Biblioteche Italiane e per le Informazioni Bibliografiche* of *Ministero della Cultura* in Italy. We note that, at the time of writing of this article accessing the data through the Internet Culturale portal may be slightly challenging due to the lack of an English version of the portal. However, we note that it is straightforward to locate the observations in the website's database with a simple search based on the information stored in Table 3 or by date (since the data are stored there based on the date of the observation). We also note that both the original observations and newly produced digital images derived from them are accessible by request to the INAF OAR director. Finally, we will aim to make the same data also accessible through the INAF OAR portal in the future, provided that their origin and derivation as specified in the present manuscript are properly acknowledged. More details will be provided in future papers based on analysis of Secchi's observations.

Table 3 lists the documents of the Secchi collection in the INAF OAR archive, with information on their position (shelf mark) in the archive, while Table 4 lists the position in the

[13] https://www.internetculturale.it/it/64/partner/29648/biblioteca-e-archivio-storico-dell-osservatorio-astronomico-di-roma

archive of the documents shown in Figures 1–10 and the filename of the corresponding digital images. Note that the time interval specified in the title of some documents does not match the one of the solar data therein.

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