Solar aureoles caused by dust, smoke, and haze

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The forward scattering of sunlight by atmospheric aerosols causes a bright glow to appear around the Sun. This phenomenon, the simplest manifestation of the solar corona, is called the solar aureole. Simple methods can be used to photograph the solar aureole with conventional and digital cameras. Aureole images permit both a visually qualitative and an analytically quantitative comparison of aureoles caused by dust, smoke, haze, pollen, and other aerosols. Many hundreds of aureole photographs have been made at Geronimo Creek Observatory in Texas, including a regular time series since September 1998. These images, and measurements extracted from them, provide an important supplement to studies of atmospheric aerosols. © 2003 Optical Society of America

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1. Introduction

The brilliant glow that encircles the Sun is known as the solar aureole. The size and intensity of this circumsolar radiation provide information about the presence of aerosols between the Sun and an observer. Yet the solar aureole is among the least observed optical phenomena in the sky because of its proximity to the Sun and its inherent brightness.

The solar aureole is caused by the forward scattering of sunlight by aerosols. The size range and columnar concentration of aerosols can cause great variation in the size and appearance of the aureole. Because of changes in the number of particulates in the slant path between an observer and the Sun, the brightness and the apparent diameter of the aureole decrease as the Sun rises and increase as the Sun descends. Dust can cause brilliant, disklike aureoles. Summer haze and smoke cause a more-diffuse aureole. When the sky is heavily polluted by sulfur dioxide emissions, multiple scattering can cause the aureole to fill the entire sky.

Atmospheric scientists have studied solar aureoles for more than a century. The Smithsonian Astrophysical Observatory studied aureoles as part of its campaign to detect fluctuations in the solar constant. Minnaert defined the aureole as ". . . the corona phenomenon in its simplest form" and presented methods for its safe observation.[1] Coulson spectroscopically measured solar aureoles in the clear sky over Mauna Loa Observatory, Hawaii, and in smoggy skies over Los Angeles, California.[2] More recently, solar aureoles have been studied by use of conventional and digital photography and both hand-held and robotic Sun photometers that automatically scan the Sun and sky. O'Neil and Miller[3] made simultaneous measurements of the aureole and optical extinction. Tanaka *et al.*[4] devised a means for calibrating Sun photometers by simultaneous measurements of the direct solar beam and the intensity of the solar aureole.

Many authors have discussed in detail the Mie scattering that causes aureoles and diffuses sunlight. Coulson's treatment[2] is especially relevant, for he expertly combines theoretical analysis with many experimental observations from various locations, including Mauna Loa Observatory in Hawaii, a site noted for its frequency of remarkably clear skies.

My goal in this paper is to stimulate renewed interest in solar aureoles and the information that they contain through simple photographic methods that are easily implemented by professional scientists and students alike. Although digital photography is particularly well suited for this purpose, Sarah A. Mims, a tenth-grade student at New Braunfels Christian Academy, New Braunfels, Texas, has demonstrated that even inexpensive, disposable cameras can be used to acquire excellent images of solar aureoles. She has used solar aureole photographs, satellite imagery, and microscopic dust, which was collected on petroleum jelly–coated microscope slides and on filter paper by a motorized air sampler, to support her contention that the dust, which exhibits

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birefringence characteristic of quartz sand, reached Texas from the Sahara desert.[5]

2. Aureole Photography Techniques

Direct sunlight is so intense that photographs of the Sun do not show the solar aureole unless the aureole extends across a substantial portion of the camera's field of view. Proper aureole photography requires that the solar disk be occluded.

The solar aureoles presented in popular books are often photographed with objects such as a street light or a flagpole interposed before the solar disk. This method works well when an appropriate object is available, which is often not the case. Moreover, it can be hazardous for one's eyes to make aureole photographs in this fashion. That is so because it is difficult to frame the photograph without inadvertently looking at a portion of the solar disk.

For serious aureole photography, a simple hand-held occlusion device is the preferred way to block the direct solar disk. This method has the added safety advantage of not requiring the photographer to peer through the camera's viewfinder when the camera is being pointed toward the Sun. One can make a simple but effective occlusion device by mounting a spherical ball or disk on the end of a thin rod or stiff piano wire. Both the ball or disk and the support rod should be painted flat black. The ball or disk should have a diameter slightly larger than that of the camera's lens.

To make a solar aureole photograph, one places the camera on a flat surface and tilts it toward the Sun until sunlight passing through the viewfinder forms a bright spot of light on the surface below and behind the camera. The spot of light will be surrounded by the camera's shadow.

The camera is then aligned until the spot of light is approximately coaxial with that portion of the shadow that approximates the location of the viewfinder with respect to the shadow. The camera is then held in place by one hand with a finger over the shutter button. The occluding device is then held 10 cm or more from the camera until its shadow falls directly over the camera's lens. The shutter button is then pressed.

After some practice, this method of aureole photography will yield excellent aureole photographs. The photographs will be even more desirable if the photographer's fingers and hat do not appear in the finished images. Although a literature search did not disclose a description of this method, the principle is so obvious that it is probably known to other aureole photographers.

Manually holding the shadow disk or ball in place while also making sure the camera does not move can be somewhat tedious. An alternative method of blocking the Sun is to mount both the camera and the occluding device on a common platform with a backboard on which the camera's shadow will fall when the apparatus is pointed toward the Sun. The shadow device should be mounted coaxially with respect to the lens and at least 10 cm away from the lens. The one aligns the apparatus with respect to the Sun by tilting it until the spot of sunlight is aligned as described above.

These methods work well with fixed-focus cameras and automatic cameras with lenses that can be set for infinity. Cameras with autofocus lenses should be set up without the shadow device in place. One does this by pressing the shutter button only until the lens focuses at infinity but not until the shutter opens. The shadow device is then placed between the Sun and the lens, and the shutter button is pressed all the way.

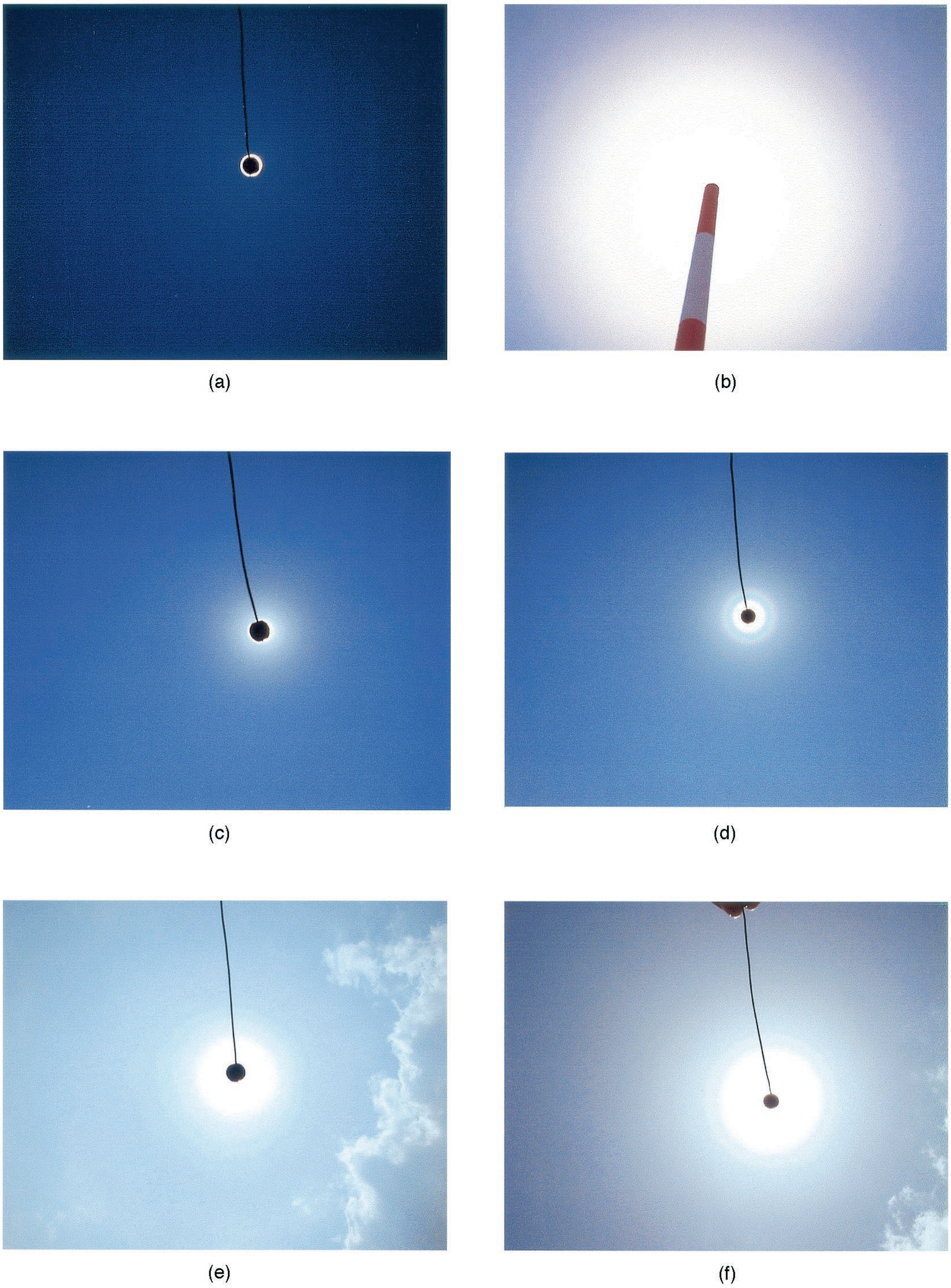
3. Aureole Photographs

Solar aureole photographs appear in surprisingly few publications. Lynch and Livingston[6] show the aureole formed on a hazy and on a clear day when the solar disk is blocked by the same street light. The revised edition of Minnaert's classic *Light and Color in the Open Air* includes several excellent photographs of coronas, including one around an aureole.[1]

Accompanying this paper are several digital photographs (Figs. 1) that illustrate the great variability in the appearance of the solar aureole that is possible. Figures 1(a) and 1(c)–1(f) were made with a true color (RGB) digital camera with a resolution of 1024 × 1280 pixels (1.3 megapixels). Figure 1(b) is a digitized scan of a 35-mm Kodachrome photograph. Unfortunately, the digital camera does not save the exposure settings. None of the photographs has been enhanced or altered, with the exception of minor cropping of Fig. 1(b).

The caption for each photograph includes the aerosol optical thickness (AOT) at 820 nm measured by LED Sun photometer[7] to provide a quantitative scale by which to judge each aureole visually. The sequence begins with Fig. 1(a), an unusual photograph of the Sun without an aureole. This image was made from the summit of Mauna Kea in Hawaii at an altitude of 4.3 km on 24 June 2000. When this image was made, the column water vapor over the mountain was less than 1 mm. This and the very low aerosol burden provided too few scattering agents to produce an aureole, and the sky appeared deep blue almost to the edge of the solar disk. Thus Fig. 1(a) is a portrait of a pristine sky in which molecular Rayleigh scattering of blue wavelengths far exceeds the multispectral Mie scattering caused by particulates.

Figure 1(b) is a quite different aureole photograph made from the summit of Mauna Kea on 4 August 1992. Hawaii, and much of the Earth, was overlain by a thick blanket of sulfurous aerosols injected into the stratosphere by the Plinian volcanic eruption of Mount Pinatubo in the Philippines on 15 June 1991. The huge aureole in Fig. 1(b) is in striking contrast to the aureole-free sky shown in Fig. 1(a). An important feature of the aureole in Fig. 1(b) is the brownish ring around its circumference. This is the rarely photographed Bishop's ring, a phenomenon first described by S. E. Bishop, a missionary in Hawaii, shortly after the volcanic eruption of Mount Krakatau in 1883.[8] Several fascinating eye-witness



(a) (b) (c) (d) (e) (f)

Fig. 1. (a) Aureole-free Sun photographed from the 4.3-km summit of Mauna Kea in Hawaii on 24 June 2000 ($\mathrm{AOT}_{820\ \mathrm{nm}} \leq 0.02$). The solar disk here and in (c)–(f) is blocked by a small black sphere mounted on a stiff wire. (b) Bishop's ring around the Sun caused by volcanic aerosols in the stratosphere photographed from the summit of Mauna Kea on 4 August 1992 ($\mathrm{AOT}_{820\ \mathrm{nm}} = 0.37$). The solar disk is blocked by an antenna mast. (c) Solar aureole on a very clear day at Geronimo Creek Observatory, Texas, 14 February 1999 ($\mathrm{AOT}_{820\ \mathrm{nm}} = 0.04$). (d) Extraordinarily rare pollen corona on a clear day at Geronimo Creek Observatory, 17 January 1999 ($\mathrm{AOT}_{820\ \mathrm{nm}} = 0.07$). (e) Broadly diffuse aureole and bluish sky caused by smoke from Mexico advected over Texas on 5 May 2000 ($\mathrm{AOT}_{820\ \mathrm{nm}} = 0.36$). (e) Disk-shaped aureole and grayish sky formed by Sahara dust blown from Africa to Texas on 4 July 2000 ($\mathrm{AOT}_{820\ \mathrm{nm}} = 0.24$).

accounts of the Bishop's ring and other curious atmospheric optical phenomena that appeared after the Krakatau eruption have been compiled by Simkin and Fiske.[9] Meinel and Meinel provide a concise explanation of the Bishop's ring, which they describe as a variant aureole.[10] The Bishop's ring in Fig. 1(b) is the only photograph in this paper made with 35-mm film (Kodachrome).

Figure 1(c) shows a small aureole in an unusually clear winter sky over Geronimo Creek Observatory (29.6° N, 97.9° W) in south-central Texas on 14 February 2000. Summer aureoles at this site are much more pronounced than the one in Fig. 1(c), but they rarely reach the size of those that can cover much of the sky in regions with significant sulfur dioxide emissions from coal-fired power plants or volcanoes such as Mount Kilauea in Hawaii.

Figure 1(d) shows an extraordinarily rare pollen corona[11] that appeared briefly over Geronimo Creek Observatory on 17 January 1999. The solar aureole is ordinarily a brilliant white. Exceptions occur when the scattering particles are the same size, as in the case of ice crystals and pollen. When an abundance of uniformly sized particles between the Sun and an observer dominates other scattering agencies, the aureole becomes separated into the colorful, concentric diffraction rings around the Sun known as a corona. Coronas formed by ice crystals are much more common than pollen coronas. The corona in Fig. 1(d) is caused by uniformly sized (~22 μm) pollen grains from juniper trees commonly known as mountain cedars (*Juniperus ashei* Buchholz). During winter the air over central Texas often carries a heavy burden of this pollen, which is notorious for the allergic reactions that it causes. Pollen coronas may be briefly visible on a few days each year or not at all.

Considerable smoke from biomass burning in Central America and Mexico is sometimes advected over South Texas. Figure 1(e) is an aureole photograph made through such smoke on 5 May 2000. The presence of thin smoke has little effect on the color of the sky. The sky in Fig. 1(e) retained its blueness, but the smoke was sufficiently thick to give the sky a washed-out appearance. Smoke in the sky over large regions of Brazil during the annual burning season causes the sky to appear brownish or gray. Near Alta Floresta, Brazil, in August and September of 1997 the AOT at 440 nm caused by smoke reached values as high as 7. When the sky is this polluted, stars and planets are invisible by night and the Sun appears as a dim orange disk that can be observed without protective glasses.

Seasonal wind storms over North Africa and China can blow dust considerable distances. Texas has often been the recipient of such dust in recent years. Figure 1(f) shows a solar aureole caused by a Sahara dust event on 4 July 2000.

4. Image Analysis

The photographs in Fig. 1 demonstrate that solar aureoles have distinctive features. Thus the experienced observer can, for example, visually differentiate aureoles caused by dust and smoke. For quantitative analysis of aureoles, one can use various computer software packages to digitally scan their images.

Previous authors have given angular dimensions and intensities for the solar aureole. Linacre,[12] for example, observes that the aureole extends to ~5° from the Sun and includes ~30% of the sky's diffuse radiation when the sky is clear and the Sun is more than ~30° above the horizon. It is now possible for observers to regard Linacre's values as first approximation estimates and to then analyze digitized aureole images to quickly make angular measurements of their own.

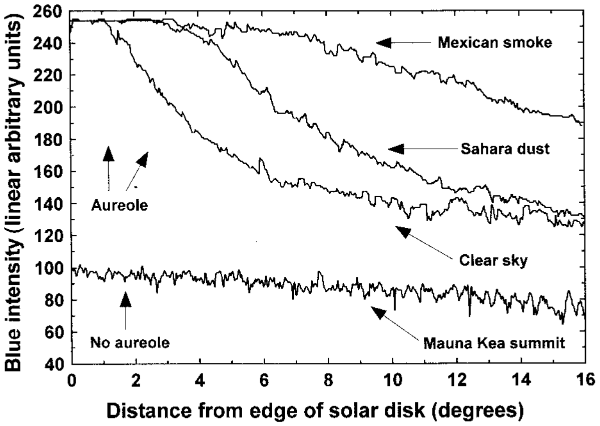


Fig. 2. Digitized scan of the intensity of blue light from the edge of the solar disk to 16° away from the Sun for the solar aureoles in Figs. 1(a) (Mauna Kea summit), 1(d) (Clear sky over Texas), 1(e) (Mexican smoke over Texas), and 1(f) (Sahara dust over Texas).

Figure 2 is a digitized scan of the intensity of blue light from the edge of the solar disk to 16° away from the Sun for the solar aureoles in Figs. 1(a) (Mauna Kea summit), 1(d) (Clear sky over Texas), 1(e) (Mexican smoke over Texas), and 1(f) (Sahara dust over Texas). The scans were made with SigmaScan Pro 5.0 image analysis software (SPSS Science), and the results were tabulated on a common spreadsheet. I measured the peak wavelengths designated blue and red by the image analysis software by placing the camera used to make the aureole photographs at the output of a spectrometer (Optronics DMCI-02). Photographs of the output slit were then made at 10-nm intervals in the blue and red wavelengths. The images were exported to a common background and analyzed by the image analysis software. This yielded a peak blue wavelength of 450 nm and a peak red wavelength of 640 nm.

The traces in Fig. 2 allow the aureoles to be more precisely defined than would be possible from a simple visual analysis. The nearly flat slope of the digitized trace of the intensity of skylight near the Sun as viewed from Mauna Kea confirms the absence of an aureole. The traces in Fig. 2 also show that the clear sky aureole over Texas [Fig. 1(c)] resembles a Sahara dust aureole more closely than it does the ultraclear sky at Mauna Kea [Fig. 1(a)]. The disk-like appearance of the Sahara dust aureole [Fig. 1(f)] and the more-diffuse nature of the smoke aureole [Fig. 1(e)] is confirmed by the sharper intensity of the former when it is compared with the latter.

Figure 3 plots the red/blue intensity ratios of the aureoles plotted in Fig. 2. The high color ratio caused by the Sahara dust implies larger particle sizes than for the smoke. Estimates of particle size

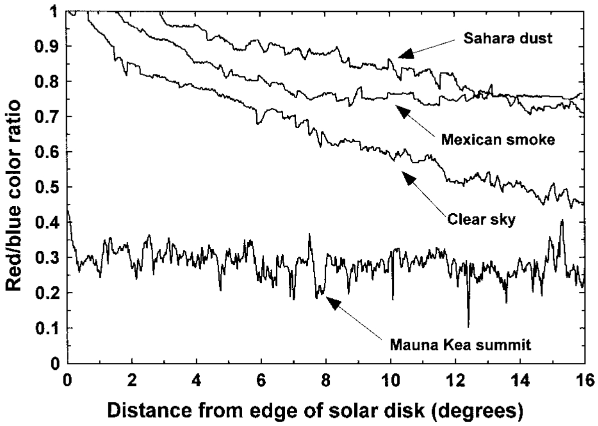


Fig. 3. Ratios of the red/blue intensities of the aureoles plotted in Fig. 2. The high color ratio caused by the Sahara dust implies that it comprises larger particle sizes than does smoke.

made by Sun photometers generally rely on interference filters' having a bandpass of <10 nm. The effective bandpass of the scans in Figs. 2 and 3 is significantly greater, of the order of >50 nm. Nevertheless, gross particle size estimates from the digitized scans method show enough promise to deserve study in conjunction with simultaneous Sun photometer observations.

The camera used for this study is fully automatic and does not permit changes in the aperture setting or the exposure time. Based on preliminary experience with a more advanced camera that records these settings, solar aureoles may be recorded with slightly different settings. Therefore a camera with fixed or manually adjustable settings would be best.

5. Conclusions

Solar aureole studies have a long history and continue today through robotic Sun photometer measurements and both conventional and digital photography. Considering that time series of daily solar aureole photographs provide a quick method for experienced observers to visually evaluate and estimate the sky's aerosol burden, the scale of current solar aureole monitoring is small. The photographic method is simple and easily implemented by both students and professional scientists. Photographing solar aureoles by use of the shadow method described here can even become a simple exercise for secondary-school students. Posting catalogs of standardized solar aureole images from around the world on the World Wide Web would permit a much better appreciation of sky conditions than tables of dimensionless optical depth numbers. Adding aureole images to time series plots of AOT would significantly enhance the value of the data by providing a visual link between the data and the appearance of the sky. It might also elicit a broader audience for such observations, as it is hoped the accompanying aureole photographs have done for this paper.

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