Energy and Environment Division

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TECHNIQUES FOR MEASURING CIRCUMSOLAR RADIATION

A. J. HUNT, D. F. GRETHER AND M. WAHLIG

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I. Introduction and Background

Circumsolar radiation refers to the light that has its apparent origin in the region of the sky around the sun. The term solar aureole is often used to describe easily observable or characteristic occurrences of circumsolar radiation. The phenomenon can easily be observed by using a finger or nearby object to block the direct sunlight from entering the eye and examining the light that streams around the occulting object. The intensity can drop off rapidly or slowly as a function of distance from the sun, vary considerably in color, or form colored rings around the sun.

Circumsolar radiation is caused by the scattering of light by small particles in the earth's atmosphere. The aerosol particles may be composed of ice crystals or water droplets in thin clouds. They may be dust or sea salt particles, smoke or fumes, photochemical pollutants, sulfuric acid droplets, solid particles with a water mantel, flocks formed of a loose aggregates of smaller particles, or any of a large variety of solid, liquid or heterogeneous materials that are small enough to be air borne. The amount and character of circumsolar radiation vary widely with geographic location, climate, season, time of day and observing wavelength. Some of the more striking cases can be observed in the presence of high, thin cirrus clouds.

It is important to distinguish between the circumsolar light that originates in the earth's atmosphere and the light coming from the atmosphere of the sun.* The confusion is compounded by the use of the term solar

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*In this discussion, zodiacal light, originating from scattering by interplanetary dust, is excluded.

corona for both cases. The light originating in the sun's atmosphere is, in most cases (except at high mountain observatories on very clear days), dominated by the scattering that takes place in the earth's atmosphere. In the following discussion it will be assumed that the circumsolar radiation is of terrestrial origin.

Some of the general characteristics of circumsolar radiation can be inferred from scattering calculations. The diffraction from a sphere may be rigorously calculated if its size, complex index of refraction, and the wavelength of incident light are known (Mie 1908; see e.g., van de Hulst 1957). If the sphere is large compared to the wavelength of light, the scattered light intensity will peak in the forward direction. If the sphere is small or comparable in size to the wavelength of light, the scattering will be more isotropically distributed in angle. For a single non-absorbing sphere the character of the angular distribution may be quite complex. However, if the calculation is performed for a size distribution of spheres and the resulting intensities added, or if the sphere is absorbing, the individual lobes of the scattering pattern disappear. Nevertheless, the same general trends with size are followed. These calculations may be applied to particles in the earth's atmosphere, but caution must be exercised. The assumption that there is just one type of uniform spherical particle with known size distribution clearly breaks down if the variety and complexity of the particles in the atmosphere are considered. The calculation is more applicable where measurements are confined to high mountains or aircraft to avoid the more complex behavior of the lower troposphere.

A number of workers have calculated theoretical circumsolar profiles based on Mie or Rayleigh scattering (Deirmendjian 1957, 1959, 1970; Eiden 1968; Green et al. 1971; Grassl 1971; Deepak 1973; van de Hulst 1977).

These calculations predict aureole profiles for spherical, homogeneous particles by assuming various size distributions and indices of refraction. In clear atmospheres the scattering is dominated by the gaseous component (Rayleigh scattering) and there is good agreement between the model and experimental data. When a substantial aerosol component is included the agreement varies. Because the aerosol composition of the atmosphere is highly variable, these models are more useful in understanding general behavior than as predictive tools.

Atmospheric aerosols have many effects on the incoming and outgoing radiation in the earth's troposphere and stratosphere. They can affect the overall heat balance of the earth, produce marked local changes in climate and affect the angular distribution of downcoming solar radiation. Accordingly, measurements of the circumsolar or aureole component of the sunlight have been performed for various purposes. Early interest in circumsolar data grew from the desire to determine the errors in the measurement of the direct beam radiation from the sun and its effect on the pyrheliometric scale (see e.g., Angstrom and Rodhe, 1966; Angstrom 1974a,b). In recent years the advent of high speed computers made it possible to use the Mie calculation in conjunction with circumsolar measurements as a sensitive probe of aerosol scattering properties. Most recently, with the upsurge of solar energy collection, interest has increased in determining the effect of circumsolar radiation on the properties of focusing collectors. This interest arises because of the overestimate of direct beam solar radiation produced by pyrheliometer measurements and the dependence of the performance of a focusing collector on the details of the distribution of light near the solar disc.

For aerosol studies measurements were generally made over larger angles from the sun, while for pyrheliometry and solar collection interest focused on the near forward scattering profile. The difference in angular range generally leads to different instrumental techniques. In the following section, general considerations in the measurement of circumsolar radiation are discussed. The final section contains descriptions of specific instrumental techniques and their regions of applicability.

II. Measurement Considerations

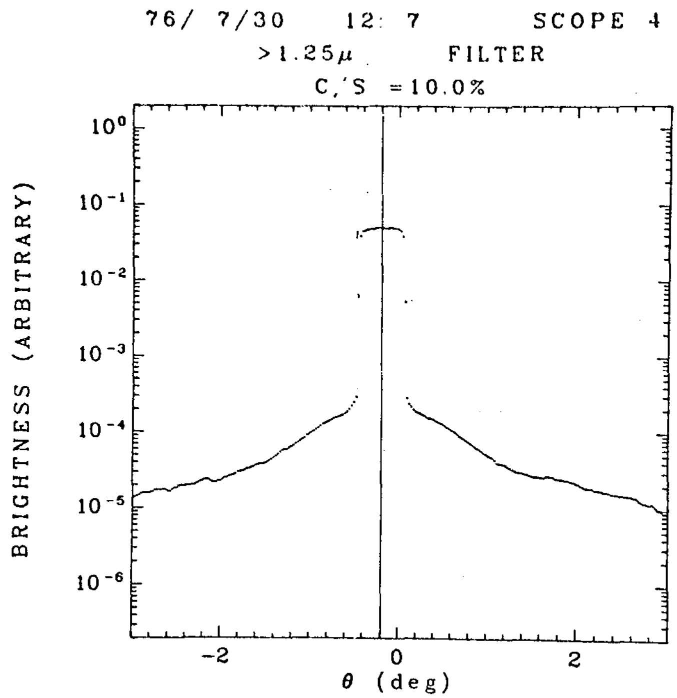
A. Angular Range - Determination of the desired angular range is one of the first considerations in the measurement of circumsolar radiation. The range refers to the minimum and maximum angle from the center of the sun that is probed by the measurement. As was discussed in the first section, these angles are related to the aerosol particle size that produces the scattering. If the sun's disc is included in the measurement, the attendant problems of detecting a wide range of light intensities and reducing the instrumental scattered light must be dealt with. Both of these problems require great care and consideration. The difficulty arises from the extreme constrast between the brightness of the solar disc and the surrounding sky. On a clear day the difference in brightness between the sun center and the sky 3^{o} away can easily exceed 5 orders of magnitude. For the same conditions the intensity of the edge of the solar disc can drop three to four orders of magnitude in less than 0.1^{o}.

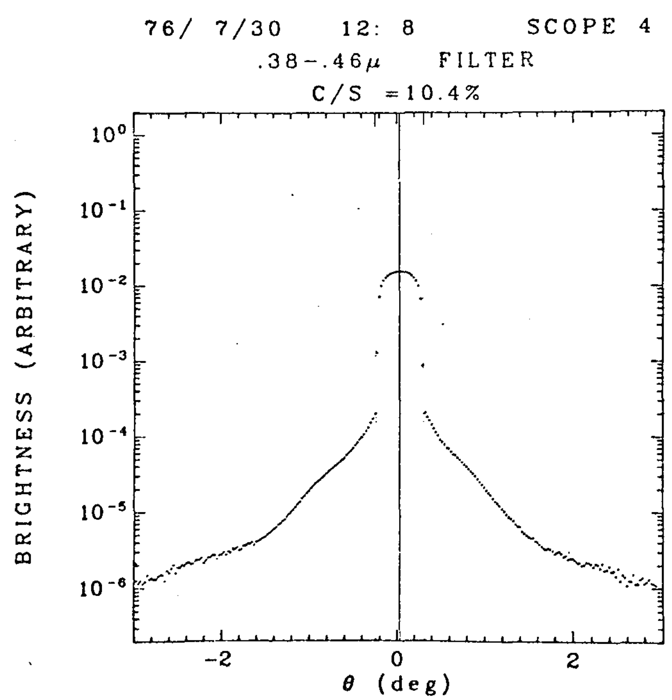
The intended use of the data will determine the maximum measurement angle. For solar energy resource evaluation pertinent to focusing collectors the maximum angle will be small, probably less than 5^{o}. In measurements that will be used for aerosol modeling calculations the maximum angle would be larger, in the range of 10^{o} - 40^{o}, depending on the needs and interests of the modeler, and it may be satisfactory to exclude entirely the light from the solar disc.

B. Angular Resolution - The angular resolution required for a measurement depends on the rate of change of sky intensity with angle. It is clear that in the vicinity of the sun the angular resolution must be much better than at some area of the sky where the intensity is changing slowly. If the angular range is chosen to exclude the sun, this resolution requirement is usually not acute. If the intensity profile at the solar disc is desired, the aperture size must be chosen small enough to obtain the desired detail. The requirement of a small aperture conflicts with obtaining a good signal to noise ratio at larger angles. In determining the effective angular resolution, the internal instrumental scattering and diffraction effects must be folded in with the purely mechanical contributions to the measurement resolution.

C. Angular Direction - For measurements that do not measure annuli about the sun but rather measure along a radius, the orientation of the radius is an additional consideration that must be evaluated in the instrumental design. The major directions would be almucantor, solar vertical, declination, or right ascension. In solar resource measurements confined to small angles the distinction is not very important except at angles very near the horizon. For use in aerosol modeling,an almucantor or solar vertical scan is preferred because of the symmetry of the scan with respect to the variation in air mass.

D. Spectral Dependence - The circumsolar intensity profile changes in magnitude and in character as a function of wavelength. Figure 1 illustrates the differences in intensity vs. angle profile for two different wavelength bands taken one minute apart by a circumsolar telescope at a desert location





XBL 772-7487

Figure 1. Computer plotted graphical displays of solar and circumsolar profiles taken just post noon on July 30, 1976 in the California desert. The dots are the individual digitations during the scan. The C/S (circumsolar/solar) value shown in the caption is defined as the ratio of the integral intensity outside the solar disc (out to 3°) to that within the disc. The wavelength pass band is also given in the figure caption.

in the southwest United States. Both the central values and the widths of the wavelength pass bands selected would depend on the application of the data. In measurements of the solar resource, the character of the receiver is important. If the receiver has the characteristics of a black body, then measurements integrating over a broad spectral range are desirable. If the receiver has a strong spectral dependence (e.g., photocells or selective coatings) more spectral selectivity may be necessary. For purposes of aerosol modeling one or more band pass filters enhance the resolution of the technique. It is rarely necessary to consider a narrow band pass measurement since aerosol properties usually change slowly with wavelength.

E. Other Considerations - One of the most important, and often overlooked aspects of circumsolar radiation, is that it changes in time. It can change as rapidly as the projection of a cloud edge can cross the detector, or it can stay nearly constant for hours. Thus, there are no easy rules to follow for timing or scheduling measurements. Figure 2 illustrates the variability of the ratio of circumsolar radiation* to direct radiation as a function of the time of day. These data were taken for the same location as that of Figure 1.

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*Defined here as the integral of the intensity from the portion of the sky bounded by the solar disc and a circle 3^{o} from the sun's center.

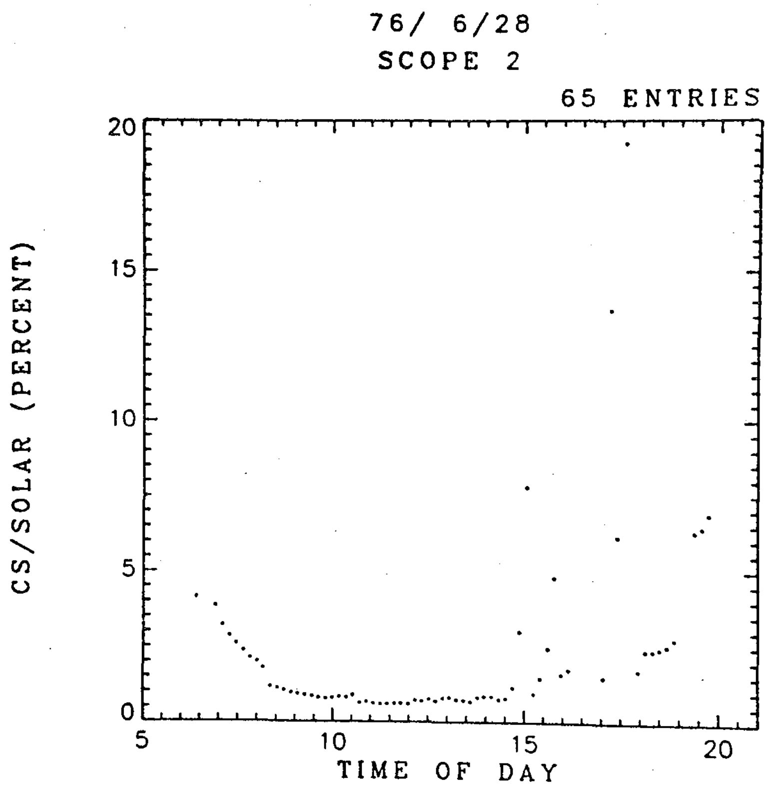

Figure 2 - Circumsolar to solar ratio as defined in the text for June 28, 1976 at Albuquerque, New Mexico.

Another factor to be considered in the instrument design for circumsolar measurement is the accuracy of tracking the sun. A simple clock-driven equatorial mount will lead to errors due to the change in the declination of the sun during the course of the day. If high resolution scans through the solar disc are desired, the tracking accuracy needs will usually require that the clock drive be supplemented with an active guidance system.

Various supplemental solar and meteorological measurements can be useful in interpreting the data. If absolute radiometric data from the sky are not an integral part of the circumsolar measurements, it is usually necessary to have simultaneous pyrheliometer measurements for calibration purposes. If the total hemispherical flux on a horizontal plane is also taken, it can be used to determine the total diffuse component of the radiation.

III. Instrumental Techniques for Measuring Circumsolar Radiation

A. Visual - Circumsolar radiation can be observed visually if some method is provided to shield the eye from the extreme brightness of the solar disc. As was previously mentioned, a finger at arms length or a nearby pole or chimney may be used. This rather crude technique provides both for monitoring the variation, and for alerting the observer to any unusual or interesting occurrences of circumsolar radiation.

Newton observed the solar aureole (he used the term corona) by studying the reflection of the sun in still water. A number of other visual techniques can be used to study the solar aureole and considerable insight into atmospheric optics can be gained by such observations (Mineart 1954). More recently, a visual classification scheme was proposed using an occulting object and a neutral density step wedge (Volz, unpublished). Another way of viewing the phenomenon by the naked eye is to study the circumlunar radiation at night. The much lower brightness of the moon makes the observation more comfortable and it can still supply valuable information about atmospheric scattering processes.

B. Photographic - A similar but less subjective measurement technique is to make a permanent recording of the appearance of the sky by using photographic film. The method has attractive features: because it is simple and inexpensive to make the record, it can offer spectral information if color film or filters are used, and record sky conditions. The two main approaches to the measurement utilize either a film with a latitude wide enough to allow simultaneous photographs of both the solar and circumsolar components and special processing techniques (Robertson and Banker, 1974) or an occulting disc consisting of a circle of neutral density filter material to reduce the intensity of the sun and low angle circumsolar light (Green et al. 1971; Ward et al. 1973). The wide latitude film technique can have over six orders of magnitude of dynamic exposure range (although published data indicates a maximum exposure variation of only about 20,000). The field of view is dependent on the optics of the camera. Green et al. used a camera with an angular field of approximately 20^o by 30^o, whereas Robertson and Banker used a longer focal length camera with a field of about 14^o by 17^o, and Ward and co-workers restricted their measurements to within 12^o from the sun.

The angular resolution of the method is dependent on the scattering, diffraction, chromatic aberration, and multiple solar images produced by the lens. If an occulting disc is not used it is very difficult to reduce the internal scattering in the camera to a low enough level to make use of the dynamic range of the film. The spectral range is limited by the response of the film and transmission characteristics of the camera optics. Several options for spectral resolution are available, including narrow or wide band pass filters and color film. The cameras can be used for occasional sampling or made automatic for scheduled measurements.

The relative ease of recording the data is strongly offset by the data measuring process. For occasional measurements the film can be developed, examined and placed in a microdensitometer and scanned. However, for monitoring purposes, the data measuring process would probably have to be automated, the film processing steps carefully monitored and ancillary time,horizon,and absolute radiation information provided on the film. In measuring the film,the brightness of most of the sky is usually discarded by making radial scans of the data in the solar vertical or almucantor planes.

For these reasons, the technique is probably most applicable to occasional measurements of unusual aureole occurrences, as a check during other measurements (e.g., pyrheliometer intercomparison), to determine scattering profiles for recurrent sky conditions, or for general survey purposes where qualitative rather than quantitative measurements are needed.

C. Scanning Aperture Instruments

The most widely used class of instruments to measure circumsolar radiation utilize a photodetector or thermopile as the detector element and use the geometry of the instrument to restrict the field of view. In recent years, photodetectors have become increasingly popular due to their sensitivity, wide dynamic range and ease of use. The wavelength response is defined by the detector and the optical components of the instrument.

In this section, the discussion treats those types of instruments that move in angle (scan) with an essentially fixed field of view. The next section describes instruments that derive the circumsolar data from changing the field of view or by comparing different areas of the sky.

There are several designs of scanning instruments that vary in the geometry of the opening and the choice of the way the angle is scanned. The detector can be exposed to the sky through a small circular opening or through a straight slit. The circular area can be scanned along various radial directions from the center of the sun or scanned raster-style over much of the heavens.

A scanning sun photometer developed for aerosol studies using the solar aureole was reported by Eiden (Eiden 1968). The sky was scanned in right ascension from 1^{o} to 15^{o} from the sun with an angular acceptance of 0.5^{o}. An open tube design with multiple baffling was used to reduce internal scattering and diffraction. The photomultiplier tubes that were used as detectors were calibrated with a standard radiation source after each set of runs. The instrument used an auxiliary photometer to measure the turbidity and to provide a signal for an active guidance system. The sky was scanned in five narrow wavelength bands from 0.448μm to 0.847μm. One scan required 10 minutes of time and was recorded on chart paper.

Three series of measurements were performed, two at high altitude stations to determine background scattering for clear continental and maritime atmospheres and one in an industrial area to study highly turbid conditions. One of the results of the work was the discovery that large (radius ≥150μm) particles played a more significant role in atmospheric scattering than had earlier been suspected, leading to a strong enhancement of the very near forward scattered radiation.

A circumsolar telescope that was designed primarily to determine the effect of circumsolar radiation on highly concentrating solar collectors was described by Grether and co-workers (Grether et al. 1975a,b; 1976a,b). The instrument was built in the form of a reflecting telescope that forms an image of the sun and adjacent sky on an aperture plate off to the side of the incoming light. The telescopes scan in declination across the solar disc from -3^{o} to $+3^{o}$ from the center of the sun. The aperture size is 1.5' in diameter when the instrument points to within 0.5^{o} of the sun center and 5' in diameter from 0.5^{o} to 3^{o}. An active solar guider keeps the tracking platform pointed accurately at the center of the sun. A fused silica window protects the mirror from the environment. A combination of baffling, light trapping, and vignetting reduce the scattered and diffracted light to a low level. A pyroelectric crystal is used as the detector element. Because of the instrument's wide dynamic range, it can make meaningful measurements of the intensity of the solar disc as well as the circumsolar region even on very clear days.

The telescope measures profiles through 8 broad band filters and through an open aperture. Simultaneous measurements are made through identical filters by an Active Cavity Radiometer (a pyrheliometer) to provide absolute intensity calibration and broad band turbidity data. Each scan takes one minute of time and the total sequence of measurements requires 10 minutes. The scan information is digitized every 1.5' of arc (every 0.25 sec) and written on magnetic tape. The system also measures the total hemispherical flux in a horizontal plane and in a plane facing the sun as well as meteorological data.

The telescopes are different than most other circumsolar instruments in that they are designed for unattended operation. They begin measurements automatically before dawn and continue until after sunset, then retrace for the next day.

A total of four telescopes were built and operated at a variety of sites across the United States to provide measurements of circumsolar radiation at locations of interest to the U.S. Solar Energy Program.

An instrument to study aerosol scattering, designed to fly in an airplane was reported by Twitty and co-workers (Twitty et al. 1976). The photometer was rotated continuously about a vertical axis, sweeping a slit shaped aperture in a complete almucantor scan, although published data only extends to an angle of $\pm 40^{o}$ from the sun. The field of view of the detector was determined by a slit in the vertical direction having dimensions of 0.6^{o} by 5.0^{o}. The instrument utilized a lens and a sun-shade to prevent direct solar radiation from illuminating the lens at angles greater than 1.5^{o} from the sun. Since the measurements were airborne it was not possible to accurately align the center of the slit with the sun. To overcome this problem, an auxiliary detector determined the actual zenith angle of the sun and a correction factor was applied to obtain the true angular radiance function. The measurements were made with a PIN photo-diode and a filter centered at a wavelength of 0.54μm. Scans were made at 30 second intervals. The output signals passed into an analog-to-digital converter and a serial tape recorder.

The photometer was calibrated by matching the output at angles greater than 40^{o} with the diffuse radiance calculated from Rayleigh theory. Auxiliary data on the aerosols were provided by a broad band nephelometer and a ground based lidar system. A series of measurements was made at various altitudes over Lake Superior in May of 1973. The consistency of the lidar and scanning photometer results lead the authors to suggest that the aureole measurements may be used to calibrate the lidar back scatter returns.

A scanning photometer designed to measure the intensity of light from any part of the sky was described by Kleckner and co-workers (Kleckner et al.,1975). The basic optics of the system consist of two mirrors in an alt-azimuth drive arrangement capable of viewing any part of the sky. The 2^{o} field of view of the optics is moved around the heavens in a series of ascending almucantor scans or swept in the solar vertical plane. The operation of the instrument is automatically controlled by a minicomputer. Any of seven broad band filters ranging in cut-off from .368µm to 1.065µm may be selected.

The instrument utilizes a silicon PIN photodetector. The position of the sun is calculated by use of an internal clock. The scheduling for the measurements is selectable, but the basic program sweeps the entire sky every 30 minutes and performs zenith and solar almucantor scans more often. The data is recorded on magnetic cassette tapes. At least six instruments are scheduled to be built and deployed in the western and northern United States.

A solar aureole radiometer was recently described by Platt (Platt, 1976). The optical design utilizes a sun shade supported by rods, two apertures and a lens. The instrument is pointed in a fixed direction and the sun allowed to transit, so the extent of the usable angular scan is dependent on the stability of sky conditions. The field of view of the photometer is about 1.4^{o}. A Barnes thermistor was used as the detector. Neutral density filters are inserted to decrease the intensity when the photometer is pointed at or near the sun. Pairs of cut-on and cut-off filters determine the spectral response of the photometer. A chart recorder is used to record the data. A series of measurements was made in April of 1975 in Melbourne, Australia to look for correlations with atmospheric turbidities.

A solar aureole photometer utilizing a slit geometry for ground based measurements was described by Lerfald (Lerfald, 1977). Basically, the instrument views a slit of the sky that moves across the sun from -8^0 to $+8^0$. The slit size and shape are varied with distance from the sun by a combination of a rotating radial slit and a linear detector. The width of the slit varies from 0.1^0 across the sun to 0.5^0 at 8^0 from the sun. The height of the slit also varies with distance from the sun. The scan can be in either the almucantor or solar vertical direction. The instrument is used with an equatorial mount and the pointing is checked hourly. The measurements are made using three wide band filters in the visible plus an open position. The silicon detector determines the wavelength response in the open position. A complete scan can be made in either 10 or 100 seconds of time. The data is converted to digital form, and written on magnetic tape. The instrument has been used in field measurements with a wide variety of lidar, solar, meteorological, particulate and background measurements. Several series of measurements were performed in the west and southwest part of the United States in 1977 in locations of interest to aerosol climatology.

D. Nonscanning Instruments - Some of the earliest measurements of circumsolar radiation were performed using an instrument developed by C.G. Abbot and L.B. Aldrich as part of the Smithsonian Astrophysical Observatory's program to measure solar radiation. A description of the measurement and an analysis of the data was given by Angstrom (Angstrom, 1974a,b). The instrument consisted of a shaded pyranometer that measured the brightness of the sky in a band 10^0 wide, concentric with the sun. The middle of the band was $8^{0}30'$ from the solar limb. The instrument relied on an absolute calibration and used no filters. The measurements were made over many years from two high altitude mountain stations. The results were used to study long range changes in the scattering properties of atmosphere.

More recently Jeys and Vant-Hull described an instrument to determine the amount of circumsolar radiation within three annular regions about the sun (Jeys and Vant-Hull, 1976). The measurement was made by attaching three brass collimating tubes to an Eppley normal incident pyrheliometer. The tubes were of different lengths to give full angle fields of view of 4.04^{0}, 2.86^{0} and 2.02^{0}. The instrument was centered on the sun and a turret containing the tubes was rotated and readings taken for each setting. The measurements were performed without filters and the detector was a thermopile. A complete set of measurements required about 10 minutes of time and was recorded on chart recorder. Supplemental measurements were performed with a horizontally mounted pyranometer and a Volz type sun-photometer. Measurements were taken in Houston, Texas on 8 days between April and July of 1975.

Another approach to determine aureole brightness was described by Shaw and Deehr, and utilized a photoelectric coronameter (Shaw & Deehr, 1975). The instrument operates by comparing the brightness of the sky at points 2^{0} and 6.5^{0} from the solar limb. The instrument is similar in design to a coronagraph, and utilizes occulting discs and several stops to reduce scattered and diffracted light. It can be used with interference filters and relies on 2 PIN silicon photodetectors. This instrument was used in conjunction with a sunphotometer to perform measurements in Alaska, southwestern United States, and Kenya in 1973.

There is only one instrument that is commercially available. It is a variable-field-of-view pyrheliometer built by the Eppley Laboratory, Inc.* It utilizes a single lens with a variable diaphragm placed at the focal plane. A series of baffles limits the field of view to a maximum of 6^{o}. The aperture can be reduced to a minimum of 40' of arc. Because the device is mounted on an equatorial mount the tracking must be checked frequently. The instrument has no provision for filters and uses a thermopile detector. Preliminary measurements were made in Newport, Rhode Island in the spring of 1977.

E. Other Measurements - This review has included a brief survey of the type of instruments that have been built to measure circumsolar radiation and does not pretend to be an exhaustive treatment. Some aureole measurements reported in the Russian literature have not been described here due to lack of instrument descriptions available to the present authors. However, there seems to have been a long history of interest in the aureole starting with Fesenkov in the 1930's and continuing work reported more recently by others (see e.g., Pavlov, 1965; Gorchakov and Isakov, 1974). The photographic technique has probably had more wide spread use then indicated by the few samples of measurements reported here.

Differing opinions exist on the relationship between the solar aureole and atmospheric turbidity; this subject has not been dealt with here.

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*Manufactured on request by The Eppley Laboratory, Inc., 12 Sheffield Ave., Newport, R.I. 02840, U.S.A.

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