Light Sources in the 0.15–20-μ Spectral Range

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The different kinds of light sources available for the 0.15–20-μ spectral range are surveyed. Information was obtained from the published literature, unpublished reports, light source manufacturers, and also from individual persons. The aim has been to present sufficient information, where available, to show the relative advantages of different sources—intensity, stability, and output uniformity were of prime interest. Continuum and line sources are included but lasers and pulsed sources are omitted. The sources are described under the main headings: Arc Discharge Sources, Glow Discharge Sources, and Incandescent Sources, with another section, Miscellaneous Sources, to cover some which could not be included under the first three headings.

I. Introduction

This paper is an extension of a survey which was undertaken in support of a continuing program at the George C. Marshall Space Flight Center, NASA, in which a remote sensing technique is used to study turbulent air flows.[1] The original survey was largely confined to commercially available light sources and was reported earlier.[2] Much detail has been omitted in this paper and the subject matter has been extended to include all laboratory sources with the exception of pulsed sources, but including some repetitively pulsed sources for the uv, and lasers: the latter are such specialized devices, and there are now such a variety, that justice could not be done in a survey of this kind (several review articles on lasers have appeared in the last few years, some of them in this journal).

The aim in this paper is to describe the different kinds of sources which exist or have been described in the literature, along with variations and improvements reported later. Construction details are omitted but may be obtained from the literature cited. In the original survey, particular emphasis was placed on source performance in the form of the following characteristics: (1) emission intensity—spectral steradiancy (W sr^{-1} cm^{-2} nm^{-1}); (2) uniformity—across the source as well as a function of angle; (3) drift—long term; (4) ac ripple in dc sources; (5) random fluctuations; (6) lifetime. When the above information is available this is indicated, but most literature sources limit such data to emission intensities, often only relative.

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Reviews of light sources have been made in the past and four of these complement the present one: Wolfe[3] (ir), Carlson and Clark[4] (visible), Koller[5] (uv), and Samson[6] (vacuum uv). Another brief review is given by Kessler and Crosswhite.[7] Use has been made of some of the material presented by these authors in order to achieve perspective, or to expand on a topic, but a minimum of duplication has been sought.

The survey is divided into sections on arc discharges, glow discharges, and incandescent sources, followed by a miscellaneous section of sources not covered by these headings. The division between arc and glow discharges is not always a clear one but this breakdown was found to be convenient. In the final section a summary is given of the general utility of the sources discussed as regards intensity and stability. (These quantities are summarized for several types of sources in Figs. 9, 10, and 11, which are referenced repeatedly throughout the paper.)

II. Arc Discharge Sources

Arcs as light sources owe their usefulness either to emission from the hot gas or to incandescence of the electrodes, and examples of each are given below. General descriptions of different kinds of arcs which have found application in the laboratory have been given by Finkelnburg and Maecker,[8] Maecker,[9] and Lochte-Holtgreven.[10] Arcs are often found to exhibit fluctuations and instabilities which render them unsuitable in many applications and it is only by exercising considerable effort and ingenuity that highly stable arc sources have been constructed.

A. Compact Arcs (Short-Arc Lamps)

The arc is contained within a fused quartz envelope and is struck between two electrodes of tungsten, or thoriated tungsten for the higher power arcs; the arc gap is usually in the range 0.1–5 mm. The gas or vapor

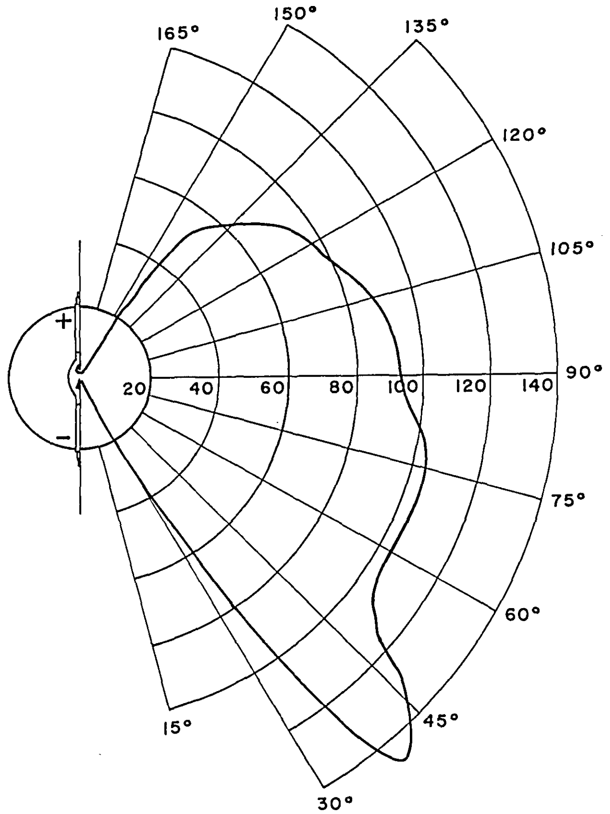

Fig. 1. Polar diagram of emission intensity for General Electric XE 5000 (5000 W lamp). Notice effect of anode emission.

fill is at a high pressure during operation (20–40 atm) which results in a high luminous (visible) efficiency. There are also some mercury capillary arcs available which operate at pressures in excess of 100 atm, close to the limit set by the quartz envelope. The early history, theory, and construction has been described by Elenbaas,[11] for mercury lamps, and by Cumming[12,13] for xenon lamps; details of commercial lamps are available elsewhere.[2,4] These lamps operate up to high-power levels (e.g., PEK Labs Inc. cover the 15 W–20 kW range) and may require special cooling.[15–17]

The high brightness of the compact arc lamp is due to its high temperature. The mercury vapor arc operates in the 5000–7000 K range,[11] and xenon arcs have color temperatures around 6000 K, with true temperatures, in the hottest regions, of up to 9000 K (see Refs. 14 and 18). The lamps are normally available filled with xenon, mercury and xenon, or mercury; some mercury lamps also contain a small amount of argon to assist in starting. Compact arc lamps with special gas fills are available commercially on special order, and those studied include neon, argon, krypton, and combinations of xenon or krypton with mercury, cadmium, and zinc.[19] Some differences were noted in the spectral energy distribution: notably, increased ir emission with neon and enhanced blue and uv emission with a mercury–krypton–cadmium fill. Enhanced emission at 530 nm has also been obtained by adding thallium iodide to mercury arc lamps.[20] For improved performance in the uv, it is possible to obtain these lamps with suprasil quartz envelopes.

Capillary high-pressure mercury arc lamps are described in the commercial literature of PEK Labs Inc. and the General Electric Co.[21] The best known types are the A-H6 (1 kW, water-cooled) and the B-H6 (900 W, cooled by high-pressure air). Typical arc sizes are 2.5 cm long and 0.1–0.2-cm diam; lifetimes vary from 5 h (for a 2-kW arc) to 75 h for the A-H6. More details of these lamps are given by Carlson and Clark[4] and by Koller.[5] A comparison between the spectral outputs in the uv of the A-H6 and other sources is given by Baum and Dunkelman,[22] which shows the A-H6 to be rather more intense than the xenon arc down to 240 nm, but below this it is weaker.

The shape of the electrodes has considerable influence on the radiative output characteristics. The brightest arcs are the small ones, operating with a very short gap, e.g., the Hanovia 959C has a gap of 0.6 mm. In general, the brightest lamps also have the greatest nonuniformity across the source and so are not necessarily the most suitable for a given application, even though high brightness may be required. Apart from those arcs having three electrodes (a third electrode is sometimes used for starting), the radiative output is cylindrically symmetric, but variations are found in the planes which include the lamp axis. These variations are not symmetric, both because of the nonuniformities in the arc and also because radiant emission from the electrodes may be significant; see Fig. 1 and similar curves[4] (others may be obtained from the manufacturers) which show the effect of electrode shape and spacing on the brightness contours. It seems that there is little available information on the wavelength dependence of these contours—Baum and Dunkelman[22] show contours for a xenon arc at a wavelength of 330 nm, but without any comparisons with other wavelengths. (Figures 9 and 10 show the spectral steradiancies of a mercury and a xenon arc compared with other sources—the emission is averaged over the visibly emitting region.) The spectral energy distribution is found to be fairly insensitive to operating power,[23] Duncan, Hobbs, and Pai have made measurements on several xenon and mercury–xenon commercial arcs and give curves of spectral steradiancy for different operating powers.[24]

For some applications there may be advantages in operating such lamps in a vacuum. This usually leads to early rupture due to overheating of the electrode seals. The manufacturers consulted had not had direct experience of this but believed that the lamps would operate in a vacuum if the seals were cooled,[18,23] but with loss in lamp lifetime. Vacuum tests on a 2.2-kW Hanovia xenon lamp made at the Jet Propulsion Laboratory showed that the power had to be reduced.[19] At the rated power the lamp life was only 59 hs: failure was catastrophic and was preceded by total envelope blackening (the lower seal attained a temperature which was 150 K higher than that found under normal operation).

Operation of short-arc lamps at higher than the rated power is possible but with reduced life. Laue[19] found that operation of a 5-kW lamp at 6 kW reduced the useful lamp life from 400 h to 100 h, and Osram[18] report electrode deterioration and loss in arc stability when operated with short duration pulses at greatly increased current.

In the selection of a light source, stability is an important criterion. The emission intensity should remain constant in time: the arc should not wander over the electrodes and it should restrike at the same location after a period of extinction, in order to facilitate optical alignment. Power-supply ripple is not a serious factor since this can be reduced as required. Furthermore, the ripple in the light output may be appreciably less than that in the current (e.g., Howerton[25] reports that a 4% ripple in the current gives rise to $\frac{1}{2}$% ripple in the emitted radiation, although others have found the two to be about the same[18,23]).

Some types of arc are more stable than others, for example the Hanovia 901C is reported to be relatively stable with short-term fluctuations of less than 2%, but with the Hanovia 959C, which has a particularly small electrode spacing, the arc sometimes jumps from one location on the cathode to another, possibly 0.04 cm away[23]—the arc is fairly stable initially and this effect starts after the first few hours of operation. (Wasserman[26] reports similar arc wandering for the Hanovia 901C.) This phenomenon of arc wandering, and restrike at a different location, has been shown to be fairly general[23,26–28] and can contribute markedly to observed intensity fluctuations (±10% in a few seconds, ±40% in 10 min[27]); it has also been found that considerable improvement is obtained after 200 h to 300 h of operation (ageing). A pulsation of the arc has also been observed[23]: the arc remains in one spot but shows radial expansions and contractions, and there may be sudden changes in intensity. Measurements do not appear to have been reported on mercury arcs, although it seems that these are more stable than the xenon arcs.[25] Improved stability of either source can be obtained by using special power supplies,[29] or by employing feedback of the measured light output to control the lamp current.[28,30]

B. Carbon Arc

The high brightness of the carbon arc makes it an attractive light source, especially for the uv and ir. During operation, a crater depression is formed at the tip of the anode and this is viewed directly for the brightest source. The gases in the arc stream are hotter than the positive crater but normally have a much lower emissivity. At high-current densities the anode spot spreads over the entire tip of the anode and leads to rapid evaporation; with suitable additives to the electrodes, such an arc produces a very intense flame—this is the Beck arc.[8]

The temperature of the arc depends on the radiation conditions. A strongly radiating arc tends to be cooler, thus a 200 A Beck arc has a temperature of 6000–7000 K in the anode flame, while a carbon arc at the same current with a scarcely luminous flame attains temperatures of 11 000–12 000 K in the anode region.[8] The temperature of the carbon crater is lower. From the measured brightness, Finkelnburg and Latil[31] deduced an equivalent blackbody temperature of 5400 K for the positive crater of a high-current arc, although the relative spectral energy distribution suggested a temperature of 7000 K. This arc had a highly luminous flame which emitted more than 50% of the total radiative output of the arc. The theory of high-intensity arcs is given in an earlier paper by Finkelnburg,[32] and by Harrington.[33] The latter discusses the effects of additives in the carbons.

The spectral distribution of the emitted radiation depends on the region of the arc viewed, on power dissipation, and on the nature of the carbons. Data on the spectral emission characteristics of the various types of carbons can be obtained from the National Carbon Company: Koller has summarized these in his book[5] and reproduces several curves. The most noticeable feature is the strong emission from the CN violet bands, having a maximum intensity at a wavelength of 388 nm, but also present are band systems of C_2, N_2, and N_2^+. The different carbons cause most changes below 500 nm, but enhanced emission around 700 nm is obtained with strontium-cored carbons.[5,33] In another paper Jayroe and Fowler[34] report on the effect of the arc atmosphere on the appearance of the emission spectrum. They studied nitrogen, carbon dioxide, air, helium, argon, and mixtures of these. It was found that with helium and argon most of the band emission disappeared. In the presence of argon a strong clean continuum extended from 360 nm down to the 247.8-nm carbon line.

In 1940 MacPherson published a paper[35] describing the properties of the low-current carbon arc and indicating its suitability as a radiation standard, with an intensity much greater than the tungsten lamp. More recently other authors have published work on the same theme.[36–38] In this connection Jaffe[39] has operated a microscope illuminator arc at 7 A, with 6-mm electrodes, and claims properties as good as those obtained by MacPherson with the larger arc.[35] Null and Lozier describe in detail the operation and properties of the low-current carbon arc, and give a set of conditions for optimum operation; an arc based on their work is now made by the Mole-Richardson Company. The positive crater of the carbon arc is a source of high intensity, good uniformity[36,38] and good reproducibility—measurements on twenty-one positive electrodes, out of six batches, gave brightness temperatures at 655.0 nm which all lay within 3797 ± 11 K.[38] Null and Lozier obtained an emissivity of 0.96–0.98 μ in the 400-nm to 4.29-μ spectral range (these authors distrusted their results beyond 4.29 μ) and Shurer's results[40] agree.

The spectral steradiancy of the low-current carbon arc has been measured by Johnson,[41] using the same type of arc as MacPherson. Johnson's results are shown in Fig. 2: these show the sharp cutoff due to air below 190 nm, and strong carbon lines at 193 nm and 247.8 nm. In the figure, the solid line represents

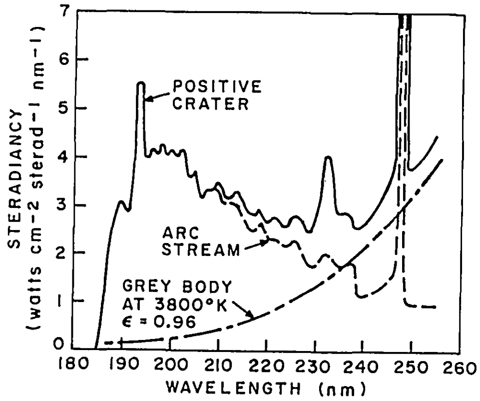

Fig. 2. Spectral steradiancy of low-current carbon arc in the uv.[41]

radiation from the arc stream as well as from the incandescent anode. The broken line is for radiation from the arc stream only (viewed 1 mm in front of the anode) and shows that this is the major contributor at these wavelengths. Emission intensity data for wavelengths longer than 4.2 μ have been reported by Rupert and Strong,[42] who compared the relative intensities of the carbon arc and the globar, operated at 1175 K (see Fig. 3). The arc emission profile shows absorption due to H_2O and CO_2 as well as a broad, shallow absorption feature around 10 μ which was not identified. The spectral steradiancy of the Mole-Richardson arc has been measured by Hattenburg for the spectral range 210–850 nm (Ref. 37): his results show a continuum which follows the emission of a blackbody at a temperature of 3792 K, within 2%—line and band emission are superposed on this continuum.

Brightness distributions across the arc crater have been published for the high-current carbon arc[31,33] and for the low-current arc.[36,38] Stability measurements have been reported by several authors. Jayroe and Fowler[34] found that within a 5-sec period, very considerable intensity fluctuations (of millisecond duration) occurred with the carbon arc operating in air; operation in an argon atmosphere improved the steadiness of the arc. Lee and Lewis[38] report temperature variations of up to 10 K during the useful life of a carbon; short-term radiation fluctuations (measured with a time constant of 1/6 sec) showed an equivalent standard deviation of 3 K. The Mole-Richardson Co. quotes long-term variations as equivalent to a temperature change of 12 K, measured at a wavelength of 650.0 nm, and short-term as 2 K: noise ($\geq$ 6 Hz) as 3 K. Translated into intensity fluctuations, this is approximately a noise level of $\pm$1%, and a drift of $\pm$2½% (for an unspecified time period).

Commercial projection arcs have been investigated for use in solar simulation, these are high-current arcs. Measurements on the Genarco Model No. ME4CWM (205–235 A) arc were made by Alexander[43] who gives curves showing uniformity of irradiance and stability. The Strong Electric Corporation arcs have been studied by Duncan, Hobbs, and Pai[24]—Jetarc, 145-A dc; U-H-1 arc, 175-A dc; Magnarc, 60 A dc—and curves of spectral steradiancy are given for the visible spectral region.

C. Argon Arc

Argon arcs are widely used in the laboratory and their properties have been described by Goldman,[44] Olsen[45,46] and others. Olsen's arc was specially built to have the high stability required in quantitative spectroscopic studies. It operates at 400 A in 1.1 atm of argon between a thoriated tungsten rod cathode and a copper plate anode. Mass loss from the electrodes was negligible during 100 h of operation. The measured arc voltage varied by less than 1% over day-long periods of operation, and it was possible to extinguish the arc, replace the cathode, and restrike with the measured voltage and radiation intensity within $\pm$3% of the previous value. Measured absolute spectral line intensities at the beginning and end of a 2-day period of continuous operation were also reproduced within $\pm$3% of their maxima. Olsen ascribes the good stability primarily to the high purity of the gas comprising the plasma and to the favorable volt–amp characteristics of the arc and power supply. In conjunction with the high-emission intensities obtained, these are attractive features for a light source. There is the usual drawback with an arc that the large-temperature gradients cause poor uniformity of emission across the effective emitting area.

The very high temperatures encountered in the argon arc suggest that it might be a useful source for the uv and vacuum uv spectral regions. Some approximate relative intensity calculations were made by the present author, and matched to the intensity given by

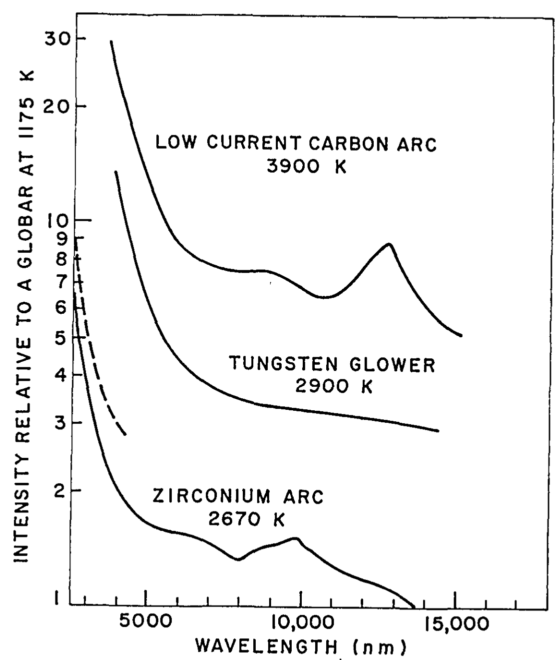

Fig. 3. Spectral steradiancies of the low-current carbon arc,[42] zirconium arc[62] and tungsten glower[174] relative to the globar; color temperatures are indicated.

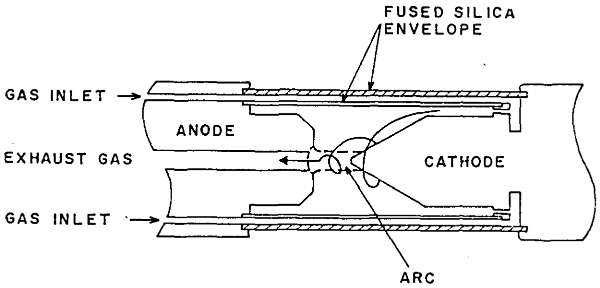

Fig. 4. Giannini vortex stabilized radiation source.

Olsen for a wavelength of 553.5 nm. The result of this calculation is shown in Figs. 9, 10, and 11. Selfabsorption of radiation was neglected so that these curves represent upper limits only; however, they do suggest that the source may prove valuable in the uv and ir.

The argon-arc spectrum shows many strong emission lines of ArI and ArII superimposed on a continuum. By introducing suitable powders into the gas feed to the arc, it is possible to excite emission lines of a variety of materials,[47] providing intense emission at new wavelengths.

A commercially available argon arc is the "vortex stabilized radiation source" (VSRS), made by Giannini Scientific Corp. This source is available in various models operating in the 5–150 kW-range (electrical). A diagram of the source is shown in Fig. 4. The arc is contained within two fused-silica envelopes. The high-pressure gas flows between these envelopes, providing thermal insulation, and is introduced around the cathode where it forms the vortex which contains the arc. The exhaust gas is extracted through the hollow anode. Figure 5 shows the spectral energy distribution curve supplied by the manufacturer which appears to have been taken at low spectral resolution, and so is a little misleading. The VSRS has been studied extensively by Neuder and McIntosh[48] and their curves of spectral energy distribution show much more line structure. These authors also give steradiancy contours for the VSRS. The angular distribution of the emitted radiation is approximately a cosine-squared function. Giannini Scientific Corp. quotes the ripple in the output radiation as less than 1% for the 20-kW VSRS and indicates that an intensity drift of less than 1% in 5 min is attainable. Random fluctuations are also given as less than 1%. Neuder and McIntosh found the stability over several hours to be around ±2%. The lifetime (of the 24-kW source) is in excess of 100 h without replacing the electrodes or silica tubes (which darken during operation).

Several special arcs have been constructed for operation in the vacuum uv. Boldt describes a cascade arc which is equipped with interlocks and buffer gases to maintain transparency to the radiation.[49,50] Another type is the magnetically confined vacuum arc described by Burns *et al.*,[51] which is operated at very low pressures. These elaborate techniques may not offer significant gains for the spectral region down to 150 nm; if self-absorption is not too great, a sapphire window on the Olsen-type arc should provide a source which is more intense than those normally used in the uv (see Fig. 9).

D. Hydrogen Arc

Several kinds of hydrogen arc are used as sources of uv radiation. Apart from the large, high-power devices such as those described by Finkelnburg and Maecker[8] or Lochte-Holtgreven,[10] there are the small encapsulated devices, usually operating at up to 200 W, which are available commercially. These low-power arcs are enclosed in Pyrex or fused-quartz envelopes, or may have a Pyrex envelope with quartz window, and are obtainable with either hydrogen or deuterium gas fills. Increases in output intensity by a factor of 2.5 have been claimed when deuterium is used instead of hydrogen.

The commercial lamps, such as those marketed by Beckman, Sylvania, or Oriel Optics, operate at 30 W, 50 W, or 60 W. Their construction includes a filamentary electron source for starting, placed within the cathode which is a nickel cylinder. The anode is a half-cylinder of nickel and molybdenum and both the cathode and anode have small holes opposite one another. The hydrogen continuum generated by these lamps is useful in the upper regions of the vacuum uv, where the quartz window allows them to be used down to about 185 nm; with especially thin windows they may be used to about 160 nm. The lamps emit into a cone angle of approximately 60°. Lifetimes are in the 200–500-h range (to 50% of initial output). Ripple and noise figures of around 0.1% are quoted by the manufacturers and a circuit for improved stability is described by Simpson.[52]

A more powerful lamp, built by Nester, is described by Allen and Franklin[53] and compared with other sources by Baum and Dunkelman[22]; a later version of the lamp[54] is described in a report by Amicone, *et al.*[55] This lamp is filled with hydrogen to a pressure of 0.55 torr and is water-cooled. As with the above arcs, a filament is used for starting. The discharge operates at 1–1.3 A at 56 V. In the work reported by Amicone *et al.*, stability was fairly important, so this is probably quite good although no figures were

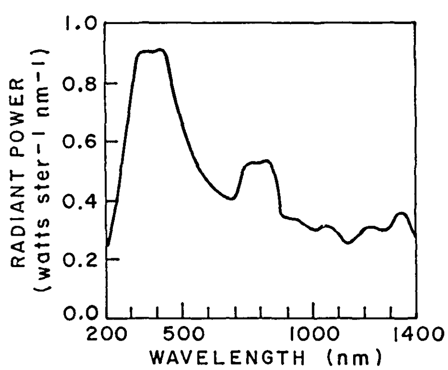

Fig. 5. Spectral intensity distribution for 17-kW VSRS viewed at 90° to the axis. Arc size 10 mm × 1.8 mm (Giannini literature).

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