SCIENCE

VOL. 79 — FRIDAY, JANUARY 12, 1934 — No. 2037

SCIENCE: A Weekly Journal devoted to the Advancement of Science, edited by J. MCKEEN CATTELL and published every Friday by

THE SCIENCE PRESS

New York City: Grand Central Terminal

Lancaster, Pa. — Garrison, N. Y.

Annual Subscription, $6.00 — Single Copies, 15 Cts.

SCIENCE is the official organ of the American Association for the Advancement of Science. Information regarding membership in the Association may be secured from the office of the permanent secretary, in the Smithsonian Institution Building, Washington, D. C.

INVISIBLE STARLIGHT[1]

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INVISIBLE radiation was first observed when Sir William Herschel, in 1800, found a blackened thermometer bulb to be warmed when placed beyond the red end of the sun's visible spectrum. The following year, J. W. Ritter noted the darkening of silver chloride caused by light beyond the *violet* end of the solar spectrum. Three quarters of a century elapsed before the study of invisible starlight was begun by Sir William Huggins, who, in 1876, photographed both visible and ultra-violet stellar spectra. Although of obvious interest, the investigation of invisible starlight has developed slowly, not only because of serious practical difficulties but because it was natural and proper to exploit first the more readily observed visible portion of the spectrum. The time has now come, however, when astronomers can perhaps afford to devote more attention to ultra-violet and infra-red light. Hence it may be worth while to outline the general importance of invisible starlight in astrophysical investigations and to review the present observational status of the problem.

To obtain a general view of the situation let us consider first radiation as it leaves the star; then what happens to it in interstellar space and in the earth's atmosphere; and finally what can be done with it when it arrives at the focus of a telescope. The original investigators had, of course, to work the sequence in the opposite direction.

The most important property of the light emitted by any incandescent object is the manner in which the energy is distributed among various wave-lengths—briefly, its spectral intensity curve. Laboratory investigations have shown that for most solid or liquid bodies the curve has a definite relationship to the

[1] Address of the retiring vice-president and chairman of the Section of Astronomy, American Association for the Advancement of Science, Boston, December, 1933.

temperature of the source, expressed by Planck's equation for a so-called black body or complete radiator. It is well known that incandescent gases in very thick layers radiate much like solid bodies, and there is good reason to believe that we may use the equation to calculate the general properties of starlight. The conclusions in the following paragraph are based largely on this premise.

The position of maximum intensity in the spectrum depends on the temperature of the star's visible surface. For the low-temperature stars (red in color) the maximum is in the infra-red; for stars of intermediate temperature, such as the sun, it is in the visible region; while for the hotter stars, like Rigel and certain other stars in the constellation Orion, it shifts into the ultra-violet. At any temperature the intensities drop rapidly on the short wave-length side of the maximum, more gradually on the long wave-length side. What wave-length range should be observed in order to include important stellar radiations? To answer this question let us assume that for any star we desire the observations to cover all points in the spectrum where the energy exceeds 10 per cent. of that at the maximum. It will be sufficient to make computations for temperatures 2,000° and 20,000° C. because the vast majority of stars have effective temperatures between these limits. For the hotter stars the maximum lies at 1450 Å, the 10 per cent. limit on the short wave-length side at 620 Å; for the cooler stars the maximum is at 14,500 Å, the 10 per cent. limit on the long wave-length side at 48,000 Å. Thus for a really complete knowledge of stellar spectra we should be able to observe from 600 Å to 50,000 Å; even to cover the maxima of various stellar spectra would require a range exceeding 1450 Å to 14,500 Å.

Except for general attrition caused by its struggle with the inverse square law, not much happens to starlight in its long passage through the abysmal depths of interstellar space. To a degree of approximation which is probably very high, except for extremely remote objects, starlight has the same properties when it strikes the earth's atmosphere that it had when it left the star. The relatively minor losses suffered through absorption and scattering in interstellar space and the reddening of light from distant galaxies, although of great interest, are not discussed here.

We are forced to study the stars from the bottom of a great ocean of air many miles deep. What this ocean does to starlight constitutes the next chapter of the story.

What it does to the more refrangible (ultra-violet) end of the spectrum is a crime. It shuts off completely all wave-lengths shorter than 2950 Å—over two octaves. This limit appears to be set by certain powerful ozone bands, and, as ozone is especially abundant in the upper atmosphere, ascending a mountain does not appreciably extend the observable range of wave-lengths. As far as we can see now, therefore, these important short wave-length stellar radiations are forever inaccessible to us unless we can establish an observing station beyond the earth's atmosphere, say on the moon. An alternative is the use of a rocket to carry a spectrograph beyond the atmosphere. Studying starlight by such an apparatus can not be contemplated with optimism at present; it even stretches the imagination to consider its application to sunlight.

The situation at the other end of the visible spectrum is not so hopeless: the long wave-lengths are mutilated but not annihilated. Figure 1 shows the

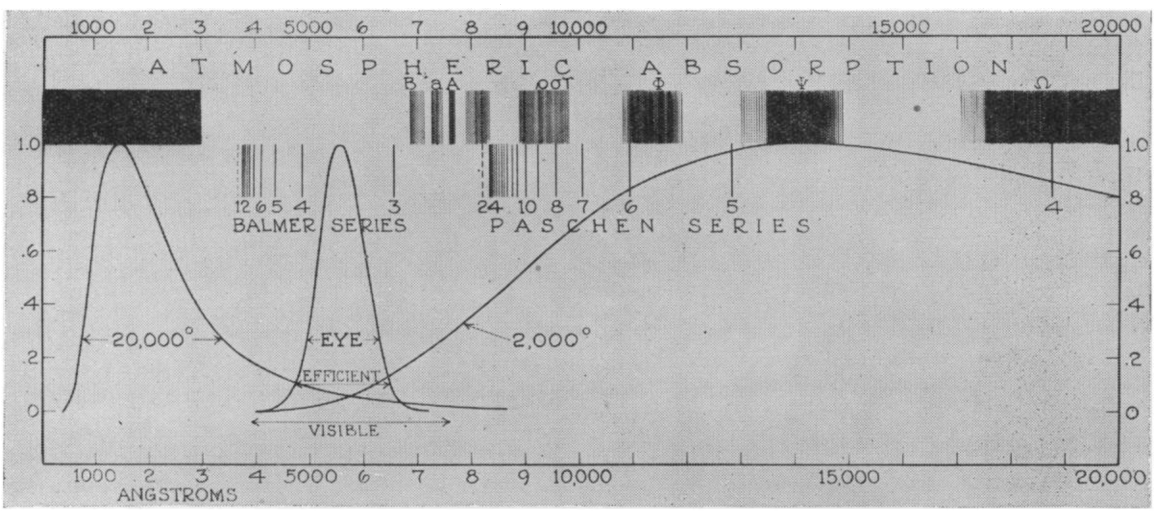

FIG. 1. Spectral intensity curves of "black-body" radiation at 2,000° and 20,000° C. compared with the visibility curve of the eye. Above: the regions of atmospheric absorption, and the positions of lines in the Balmer and Paschen series of hydrogen.

ultra-violet barrier and the regions in the near infra-red that are subject to strong absorption.

The human eye is sensitive to a band of wave-lengths—corresponding to the colors of the visible spectrum—which comprises but a small fraction of the range of wave-lengths of astrophysical importance. Fig. 1 compares the visibility curve of the eye with the spectral energy curves of stars at 2,000° and 20,000°, respectively. Notice to what a slight extent the curves overlap. Visible light extends from about 3900 Å to 7600 Å (further in both directions for very high intensities). Beyond 4740 Å on the violet side, and 6500 Å on the red side, however, the efficiency of the average eye is less than 10 per cent. of its maximum efficiency, which falls at 5600 Å in the green. The diagram also shows the very considerable regions transmitted by the atmosphere, which make no impression on the eye. In these regions the astronomer can study invisible starlight. It is an interesting fact that the visible wave-lengths lie near the geometrical mean of the limits of important radiation from the stars. The following small table, taken from computations by L. L. Holladay, shows for the two temperatures the percentages of black body radiation in various spectral regions.

PERCENTAGES OF BLACK BODY RADIATION IN VARIOUS SPECTRAL REGIONS

Temp.	Far U. V. 0 to 3000 Å	Near U. V. 3000 to 4000 Å	Visible 4000 to 7600 Å	Infra-Red 7600 Å to ∞
2,000°	0.0	0.0	1.4	98.6
20,000°	73.9	11.8	11.3	3.0

No thoughtful person will consider the fact that our atmosphere is transparent to those radiations which the eye uses in vision to be a mere coincidence; adaptation is surely indicated. Moreover, it is highly convenient that most solid objects be opaque to these same wave-lengths. X-rays penetrate both air and solids and would serve poorly for vision. Now what shall we say of the additional fact that the most intense radiations of our principal light giver, the sun, lie in the range of high visual efficiency? Adaptation is again indicated. We may, however, propose the following question: How did the human race select for its abode a planet whose atmosphere is transparent to the most important rays of the light-giving body about which the planet revolves?

The first observations of stellar spectra were of course made visually. Not until the successful application of photography in 1876 by the astrophysical pioneer, Sir William Huggins, could any of the ultra-violet be included. The most striking ultra-violet features shown by his photographs (the published reproductions of which extend to 3300 Å) were the numerous hydrogen lines extending the Balmer series to a far greater number of members than previously known. The great importance of the H and K lines of ionized calcium was also clearly brought out. Huggins found at once a definite limit in the ultra-violet and, correctly ascribing it to the action of the earth's atmosphere, explained the situation in the following words:

> There is little doubt that in stars of the white-star class, and many of the solar class, the star's light is limited in its extension into the ultra-violet alone by the absorption of our atmosphere, as I found to be the case with the light of α Cygni; however prolonged the exposure, the spectrum of this star stopped upon the plate at about the place which Cornu had found to be the limit imposed upon solar light by atmospheric absorption—namely, at about λ2970. The light of Vega, at my Observatory (which has an elevation of 177 feet), with the barometer at about 30 inches, was abruptly weakened at λ3000 and then continuing very faint, was apparently extinguished at λ2970.
>
> Within this limit, imposed upon all celestial light by our atmosphere, the character and strength of the ultra-violet region of the spectra of stars will be of the first importance in any discussion of the classification of the stars founded upon the hypothesis of an evolutional progress.

Huggins' apparatus was especially adapted to the efficient recording of ultra-violet light. His Cassegrain telescope had speculum metal mirrors, while the spectrograph was equipped with calcite prisms and quartz lenses.

In modern apparatus the two great hindrances to the observation of ultra-violet starlight are the opacity of the glass employed and the transparency of silver. A trace of iron makes optical glass, especially that containing lead (flint glass), transmit very poorly in the ultra-violet. In general, the denser the glass, the higher the dispersion and the smaller the ultra-violet transmission. The types of flint glass commonly used for prisms in astronomical spectrographs cut down the light seriously at 4000 Å and prevent, without considerably increased exposure times, extension of the spectra past 3900 Å. Quartz is beautifully clear in this region, and certain recently developed types of ultra-violet glass combine high transparency with fair dispersion. Gratings may, of course, be used in the ultra-violet, but so far have not been found to compete well with prisms, except for high dispersion.

Reflecting telescopes are free from the absorption introduced by the lens of the refractor, but the ordinary silver-on-glass mirror has a difficulty peculiar to itself, and one which has set the ultra-violet limit of spectroscopic observations with modern reflecting telescopes. A curious property of a thin silver film, such as that deposited on an astronomical mirror, is that, although almost perfectly opaque and highly reflecting to visual light, it has a transmission band near 3200 Å. Starlight of this wave-length, therefore, shines right through the silvered surface of an astronomical mirror and is not returned with the other light to the focus. The limit thus set is shown by the fact that W. H. Wright, using an efficient ultraviolet spectrograph in connection with the Crossley silver-on-glass reflector at the Lick Observatory, was able to photograph the spectrum of α Cygni only as far as 3245 Å.

Speculum metal, formerly widely used for astronomical mirrors, is more uniformly reflective in the ultra-violet than silver. More modern substitutes are chromium or aluminum. Mirrors with surfaces of one of these metals should make possible photographs of stellar spectra out to the limit set by the atmosphere.

The first agency to explore the infra-red of stellar spectra as well as of the solar spectrum was not photography, but an energy-measuring device equally sensitive to all wave-lengths. Moreover, an instrument of this kind is able to tell us something of wave-lengths much longer than anything the photographic plate can as yet record. It will be convenient, however, to speak first of what has been accomplished by photography in the near infra-red.

The first photographs of stellar spectra, as already mentioned, were limited to the blue-violet region to which alone the older emulsions were sensitive. Later the application of photo-sensitizing dyes, notably erythrosin, pinacyanol and dicyanin, made possible the inclusion of longer wave-lengths. For a number of years preceding 1920, stellar spectrograms were frequently made on ordinary emulsions sensitized shortly before exposure by staining with one or more dyes. Since 1920 commercial panchromatic plates, in which the dye is incorporated in the emulsion before coating, have been greatly improved, and are now very satisfactory for the region from 5000 Å to 6800 Å. For exposures to stellar spectra they are usually hyper-sensitized by a preliminary bath in dilute ammonia.

Before 1930, special photographic emulsions were available for the extreme red and near infra-red, but they were relatively insensitive, and considerable difficulty was experienced in obtaining useful stellar spectrograms beyond about 7000 Å. A few photographs, however, were made by V. M. Slipher, J. Bosler, W. H. Wright and P. W. Merrill on plates sensitized with dicyanin, kryptocyanin or neocyanin.

The recent discovery and systematic testing of new dyes, particularly by the Research Laboratory of the Eastman Kodak Company, has resulted in greatly improved emulsions for the longer wave-lengths, and it is now possible to obtain, with moderate exposure times, satisfactory stellar spectrograms extending into the infra-red as far as 9000 Å.

In the region from 7000 to 9000 Å, lines of the earth's atmosphere are numerous and intense and interfere considerably with the observations of stellar lines. There are, nevertheless, many features of interest, especially in the clear region 8320–8900 Å. Photographs of this region have recently been made at Mount Wilson with a small grating spectrograph attached to the 100-inch telescope. No effort was made to penetrate the dense group of atmospheric lines, beginning about 8950 Å, for, although feasible to do so, the study of stellar features would be handicapped by the intense and closely packed telluric lines. With zenocyanin plates it does not appear impossible to extend stellar observations beyond the end of this group at 9800 Å, but this has not yet been attempted.

Among the interesting features photographed in the near infra-red of stellar spectra may be mentioned the Paschen series of hydrogen lines; the great triplet of ionized calcium, λλ8498, 8542, 8662; neutral oxygen lines, λλ7771–4–5, 8446; cyanogen absorption in N-type spectra.

According to the quantum theory, a hydrogen atom must reside in one of the so-called stationary states whose energies exhibit a regular progression in inverse proportion to the squares of integers from one to infinity. Series of spectral lines are formed by transitions between any level and the succession of higher levels. Physicists have observed and named the first five series:

Series of Hydrogen Lines

Lower level	Location in spectrum	Name
1	1,200– 900 Å	Lyman series
2	7,000– 3,600 "	Balmer series
3	19,000– 8,200 "	Paschen series
4	41,000–15,000 "	Brackett series
5	74,000–23,000 "	Pfund series

The Lyman series lies entirely in the far ultra-violet inaccessible in stellar spectra while the Brackett and Pfund series are deep in the infra-red, where present methods are inadequate to record lines in stellar spectra. The Balmer series is favorably situated and has been so extensively studied since the days of Sir William Huggins that its behavior is well known and need not be described here.

It may be useful to summarize previous observations of the Paschen lines. Laboratory observations of the first two lines m = 4, 5, λλ18751, and 12818 Å, by Paschen himself, using a bolometer, were reported in 1908. About fourteen years later, F. S. Brackett, working at Johns Hopkins University with a sensitive thermocouple constructed by A. H. Pfund, found 3 or 4 additional lines. The first photographs of Paschen series lines were made a few years later at Johns Hopkins by A. H. Poetker on neocyanin sensitized plates prepared by the Eastman Kodak Company. The lines λ10049 (m = 7) to λ8863 (m = 11) were included.

The first astronomical identification was the line λ10049 made by H. D. Babcock on his photographs of the solar spectrum and on the bolometer tracings of Abbot and Freeman. Babcock also suspected the presence of the preceding line λ10938 on the bolometric record. Recently, H. W. Babcock has found nine members of the Paschen series, λ9546 (m = 8) to λ8502 (m = 16) inclusive, as diffuse emission lines on spectrograms of the solar chromosphere made, without an eclipse, at the 150-ft. tower telescope of the Mount Wilson Observatory.

The first spectrograms to show these lines in stellar spectra were taken in June, 1932. Since then numerous photographs showing lines from λ8862 (m = 11) to λ8334 (m = 24) have been obtained. The appearance and general behavior of the Paschen lines in the various types of the stellar sequence is much like that of the corresponding Balmer lines. They are conspicuous in A-type spectra, especially in the "c" stars β Orionis and α Cygni.

The ionized calcium lines λλ8498, 8542 and 8662, like the related lines H and K in the violet, are prominent through a range of spectral type from A to M and constitute convenient landmarks in the near infra-red. The infra-red lines arise from a metastable D term and thus tend to exhibit, in absorption, the properties of ultimate lines. The general behavior in stellar spectra is therefore much like that of H and K, but some interesting exceptions occur. The facts suggest that among the hotter stars high luminosity enhances H and K with respect to the infra-red lines, while among red stars the reverse relationship holds.

The interval of spectral type through which the neutral oxygen line λ8446 and the triplet 7771–4–5 have considerable intensity is about A0–G0, but these lines appear very sensitive to absolute magnitude. They are more intense in α Cygni than in any other object photographed. The presence of these lines in emission in γ Cassiopeiae and P Cygni strengthens the correspondence between atmospheres of Be stars and the solar chromosphere.

Lines accentuated in the infra-red spectrum of α Cygni, possibly in consequence of the star's high absolute magnitude, are those of H, O I, N I, Mg II. These lines should prove valuable in the problems of high-luminosity stars of types B–G.

The region from 8320 to 8840 Å in spectra of classes K and M is dominated by lines of three elements, calcium, titanium and iron. Calcium is represented by the triplet of ionized lines, titanium and iron by numerous lines of the neutral atom. The only notable line not due to one of these three elements is λ8806 of neutral magnesium.

The characteristic bands in N-type spectra have, for many years, been ascribed to carbon or cyanogen. Identifications of additional cyanogen bands in the extreme red and infra-red have been brought out by recent photographs at Mount Wilson. It therefore seemed desirable to ascertain whether details of the complex stellar spectra, almost wholly unidentified except for band-heads, correspond with groups of individual band lines. For this purpose Dr. King kindly offered his photographs of furnace spectra, from which were prepared positive copies with the scale reduced to that of the stellar photographs. Direct comparisons of the stellar negatives with the laboratory positives yielded convincing evidence that a very large part of the extraordinary structure in N-type spectra between 6910 and 8780 Å may be attributed to absorption by cyanogen molecules. Many, and perhaps all, the apparently bright lines are only bits of continuous spectrum emerging through narrow interstices in the complex network of absorption lines. As Dr. Sanford has since found that this explanation is true also of the regions of shorter wave-length, the well-known difficulty experienced by previous observers in making chemical identifications of the narrow maxima as emission lines is understandable.

Time allows only a bare mention of the extremely interesting recent investigations of the infra-red spectra of the planets. Slipher, whose earlier work on the visual region of planetary spectra is well known, photographed conspicuous dark bands in the spectra of Jupiter and Saturn near 7920, 8400, 8615 and 8810 Å. His spectrograms extended beyond 10,000 Å. Observations by Adams and Dunham in the infra-red have revealed the presence of carbon dioxide on Venus, and, in confirmation of probable identifications by Wildt, of ammonia and methane on Jupiter and Saturn.

We now turn to longer wave-lengths which can not yet be photographed. It is not for lack of stellar energy, however, that the photographic plate is impotent. As Fig. 1 shows, the radiation of a low temperature star has far more energy per ångström between 10,000 and 20,000 Å than at the shorter wave-lengths where photographs are taken with ease. This leads us to hope that in the near future emulsions sensitive far into the infra-red may be produced. Moreover, it is possible that photoelectric cells sufficiently sensitive to the infra-red for stellar observations may soon be developed.

For the present, however, we have recourse only to measurements made by means of so-called "non-selective" receivers that react equally to a given amount of radiant energy, no matter what its wave-length. This appears not to be true of any chemical or electronic process. It is well known, however, that all radiation falling on a dull black (non-reflective) surface is transformed into heat, and the resulting rise in temperature of the receiver is a measure of the intensity of the incident radiation. The problem thus resolves itself into detecting and measuring very small changes in temperature.

A very small blackened receiver at the focus of the 100-inch telescope on Mount Wilson may be heated as much as 0.°015 C. by the image of Betelgeuse. For fainter stars the measured increase in temperature is often but a few millionths of a degree.

These small temperature differences have been successfully measured by devices of three different types: (1) the thermocouple, (2) the bolometer, (3) the radiometer. In the thermocouple the heat is conducted from the receiver to a small area of contact between two suitable metals and there generates a minute electric current, which is measured with a sensitive galvanometer. In the bolometer, the change in electrical resistance of a small metal strip exposed to the stellar radiation is measured. The action of the radiometer depends upon the rotation of a delicately suspended vane, caused by the increased rebound of the molecules of the surrounding gas when one side of the vane is warmed by starlight. Measurements of stellar radiation by the three methods have been made by various observers as follows: The thermocouple—Pfund at Allegheny Observatory, Coblentz at Lick and Flagstaff Observatories, Pettit and Nicholson at Mount Wilson Observatory; the bolometer (originally developed by Langley for measurements of the solar spectrum)—Abbot at Mount Wilson Observatory; the radiometer—Nichols at the Yerkes Observatory, Abbot and Smith at Mount Wilson Observatory. The sensitivity of these three instruments, which measure the rise of temperature in entirely different ways, is nearly the same.

Investigation of stars with these instruments is still in the pioneer stage, but numerous significant results have already been obtained. Infra-red light plays an especially important rôle in the study of low-temperature stars, many of which are long-period variables. Ultra-violet light would be equally important in observations of high-temperature stars, were it not shut out by the earth's atmosphere.

Stellar radiation measurements show that, to a first approximation, the intensity of infra-red light from cool stars is that to be expected on black body theory if temperatures deduced from observation at shorter wave-length are correct. The effect on color- and heat-indices of departures from black-body radiation, due to band-absorption or other causes, should be carefully studied.

Pettit and Nicholson, measuring with a thermocouple the energy collected by the 100-inch telescope, have discovered certain remarkably interesting facts concerning the behavior of long-period variable stars. They found for six objects the mean range in total energy to be only 0.9 mag., whereas the visual range is 5.9 mag. In other words, in passing from minimum to maximum the brightness of these stars is multiplied by 230, while the total heat radiated is only slightly more than doubled. Pettit and Nicholson also found the energy maximum to occur 50 days (about one seventh of the cycle) later than the light-maximum, when the brightness has decreased by 1.5 magnitudes (*i.e.*, to one fourth of the maximum brightness). The importance of these facts in the study of long-period variables as immense gaseous globes of fluctuating brightness is obvious.

The same observers have obtained useful data by comparing the total radiation of a star with that transmitted by one centimeter of water which screens out radiation of wave-lengths greater than about 12,000 Å. For long-period variables at minimum light the water cell transmitted less than one seventh of the total energy.

Dr. C. G. Abbot in 1923 and 1928 employed radiometers in connection with the 100-inch telescope to make measurements of the intensity at various points in low-dispersion spectra of a few bright stars. Readings were made at nine wave-lengths from 4370 Å to 22,240 Å. The data were sufficiently accurate to outline the general form of the energy curve and to show the approximate position of its maximum. Dr. Abbot thought a tenfold increase in sensitivity would justify a long campaign of observations of spectral energy-distribution. Dr. Sinclair Smith has recently devised a modified technique, which may afford the desired improvement and thus make possible the determination of accurate energy curves of numerous bright stars. Investigations of this kind, combined with reliable spectrophotometric measurements by photoelectric cells or by photography, should in the near future greatly extend our present fragmentary knowledge of energy distribution in stellar spectra, and thus be of fundamental importance in the solution of many astrophysical problems.