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In 1928 Abbot[1] constructed a radiometer with vanes 0.4 mm. wide and 1.0 mm. tall. He used fragments of houseflies' wings. The front surfaces were blackened by painting with a suspension of lampblack in alcohol, having a slight addition of shellac to fix the coating. Behind these absorbing vanes he fastened with beeswax two tiers of vanes of unpainted fly wings, to make what might be called a triple-decker system. Thus two gas spaces were left between the vanes, so as to prevent the rear surfaces from being easily warmed by radiation. The vanes were 1.2 mm. apart between centers. The total weight of his system, including its mirror, was 0.94 mg., and its moment of inertia about 253×10^{-9} g-cm.[2] With a candle at 2.4 m., one silver-on-glass reflection, two fused-quartz plates, and a thin crown-glass lens interposed, the system, at 1.5 seconds single swing, gave 80 mm. deflection on scale at 40 cm., when the candle image was shifted from one vane to the other, with a lens aperture of 3.7 mm.[2]

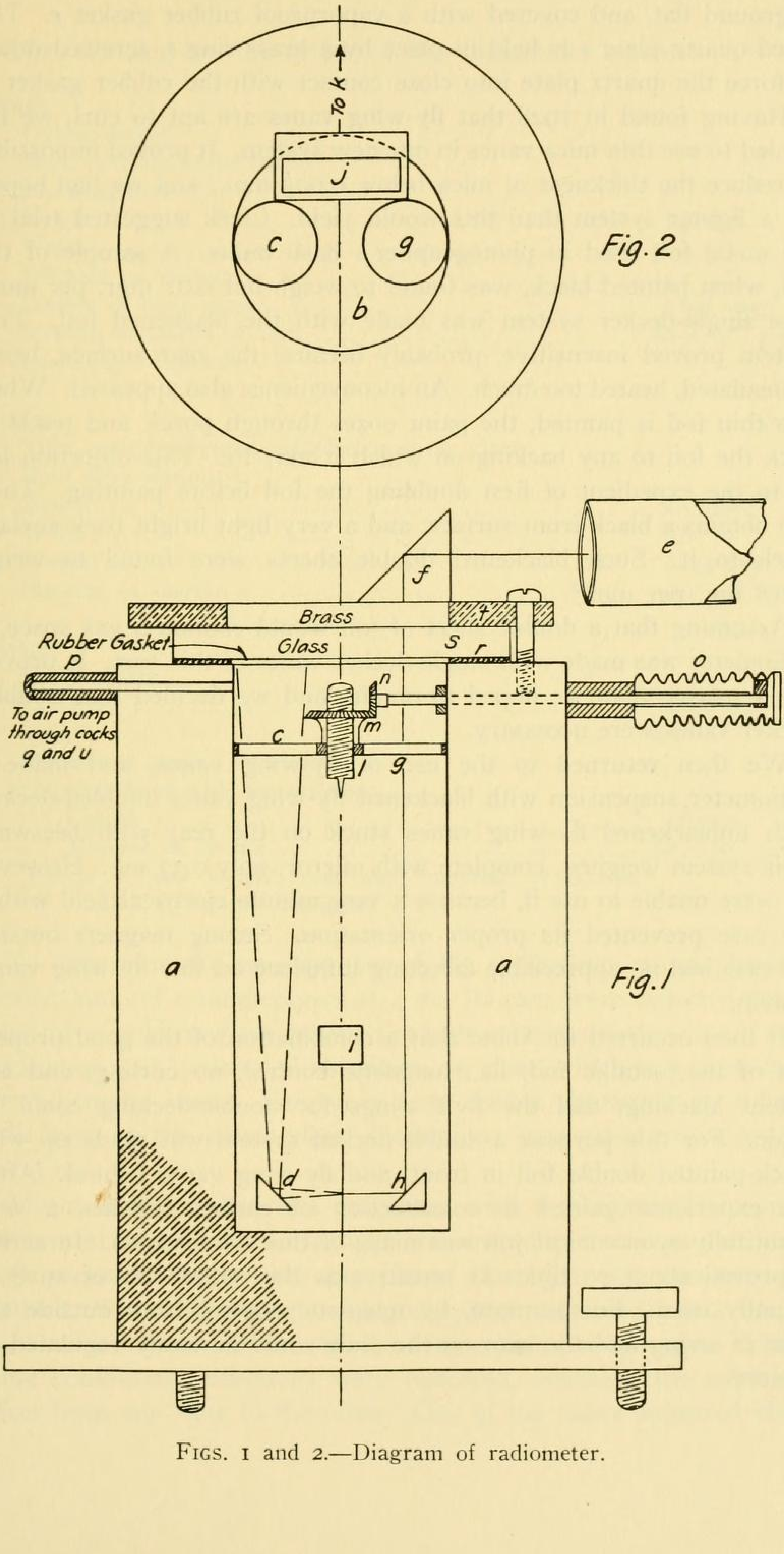
He had intended to use this radiometer at about 12 seconds time of single swing. But having cleaned fingermarks from the sealed, optically figured, fused-quartz tube in which it lay, in an atmosphere of 0.23 mm. pressure of hydrogen, he noted that electrical charges formed which could not be removed and which produced a field so strong that the time of swing was reduced as stated. Nevertheless he used the instrument in a prismatic spectroscope, having the large flint-glass prism described on page 26, volume 2 of the Annals of the Astrophysical Observatory of the Smithsonian Institution, and five silver-on-glass reflections. He observed the heat in the spectra of 20 stars whose rays were concentrated at the Coudé focus of the 100-inch reflector on Mount Wilson. The telescope at that time had three

[1] See Mount Wilson Contributions No. 380, Astrophys. Journ., vol. 69, pp. 293-311, 1929.

silver-on-glass mirrors, making eight mirrors altogether in the optical system. Owing to great prismatic dispersion and large losses of light from imperfect reflections it was impossible in 1928 to observe stellar radiation of wave lengths less than 0.423 micron. Fairly good results were obtained for yellow and red stars, but not for blue or white ones.

Hoping to undertake energy-spectrum work with white and blue stars, where the measurements to be of value must be carried far beyond the visible violet, we first undertook to construct a more sensitive radiometer, impervious to disturbance by electric charges. After many experiments with the quartz tube, some of which are described in Science of March 9, 1945, we became convinced that light radiometer suspensions cannot be used in sealed quartz tubes with any certainty of success. One unexpected result of these preliminary experiments was of much value afterward. Suspensions built of thin mica, and of some other substances not regarded as magnetic, can be deflected by magnets from without. The electrical disturbances having proved so unmanageable in sealed quartz tubes, we had recourse to a closed hollow cylinder of brass into which the radiation could be reflected vertically through a quartz plate at the top. The construction is shown in figure 1. In adopting this expedient we depended, of course, on the theorem that the electric force within a closed conductor is zero.

In figure 1, *a* is a hollow cylinder 6 in. tall, 4 in. in outside diameter, bored out within to a depth of 5 in., leaving a recess of 210 $cm.^3$ A brass plate *b*, shown from above in figure 2, admits a cone of rays at *c* to shine upon the radiometer vanes when reflected by the aluminum-on-glass mirror *d*. The adjustment is observed by the telescope *e* and prism *f* through the hole *g* and mirror *h*. A mirror *i* is adapted to reflect the recording light beam upon the tiny mirror of the system, and thence back through the slot *j* to the scale *k*. At *l* is a support with screw adjustment to fix the suspended radiometer system at the correct height with respect to the mirrors *d* and *i*. The support *l* is rotatable by gears *m*, *n*, operable from the sylphon *o*. At *p* is the outlet tube for evacuation and filling. Two cocks (not here shown) are provided, connected by a tube between, having such capacity that when this tube is filled to ½ atmospheric pressure with hydrogen, the opening of one of the cocks into the previously highly evacuated radiometer chamber sets up a hydrogen pressure of 0.23 mm. of mercury. To guard against porosity of the metal the brass cylinder *a* is tinned with solder both inside and outside. Its top



FIGS. 1 and 2.—Diagram of radiometer.

is ground flat, and covered with a vaporproof rubber gasket *r*. The fused-quartz plate *s* is held in place by a brass ring *t*, screwed down to force the quartz plate into close contact with the rubber gasket *r*.

Having found in 1928 that fly-wing vanes are apt to curl, we intended to use thin mica vanes in our new system. It proved impossible to reduce the thickness of mica below 0.005 mm., and we had hoped for a lighter system than this would yield. Clark suggested trial of the metal foil used in photographer's flash bulbs. A sample of the foil, when painted black, was found to weigh but 0.01 mgr. per $mm.^2$ One single-decker system was made with the blackened foil. This system proved insensitive, probably because the rear surface, being uninsulated, heated too much. An inconvenience also appeared. When this thin foil is painted, the paint oozes through pores, and tends to stick the foil to any backing on which it may lie. This objection led us to the expedient of first doubling the foil before painting. Then one obtains a black front surface, and a very light bright back surface stuck to it. Such blackened double sheets were found to weigh 0.018 mg. per $mm.^2$

Assuming that a double sheet of foil would contain a gas space, a radiometer was made with single-decker vanes of this sort. It proved less sensitive than we hoped to obtain, and we decided that double-decker vanes were necessary.

We then returned to the use of fly-wing vanes, and made a radiometer suspension with blackened fly-wing vanes doubled-decked with unblackened fly-wing vanes stuck on the rear with beeswax. This system weighed, complete with mirror, only 0.33 mg. However we were unable to use it, because a very minute electrical field within the case prevented its proper orientation. Strong magnets outside the case had no appreciable directing influence on this fly-wing vanes system.

It then occurred to Abbot that a combination of the good properties of the metallic foil, i.e., magnetic control, no curling, and excellent blacking, and the fly's wings for double-decking could be made. For this purpose a double-decked system was made up with black-painted double foil in front, and fly-wing vanes behind. After the experience gained in construction of earlier systems, a very beautifully symmetrical job was made of this combination. In action it proved about 20 times as sensitive as the radiometer of 1928 as actually used. Furthermore, by magnetic control from outside the time of swing and the zero on the scale could be easily regulated as desired.

The following are the details of this radiometer system:

VANES

Double-decked.
Metal foil blackened front.
Fly-wing back.

Height	1.5 mm.
Width	0.4 "
Distance on centers	1.1 "
Weight of both vanes	0.021 mgr.
Moment of inertia of both	66×10^{-9} g-cm.^{2}

Fastening: Beeswax.

MIRROR

Thin, optically-figured, microscope cover glass.
Both sides platinized.

Height	1.1 mm.
Width	0.6 "
Weight	0.135 mg.
Moment of inertia	40×10^{-9} g-cm.^{2}

FRAME

Fused quartz.

Diameter	0.004 mm.
Length	42. "

Moment of inertia: Negligible.
Crossbar fixed with burnt shellac.

Length	1.6 mm.
Moment of inertia	12×10^{-9} g-cm.^{2}

System: Total weight, 0.40 mg.; moment of inertia, 118×10^{-9} g-cm.^{2} complete.

To determine the sensitiveness of the radiometer we employed a Hefner lamp of 1 candlepower at 4 m. Its rays were reflected downward by a gold-on-glass mirror through a fused-quartz plate 8 mm. thick upon a 45° mirror of aluminum on glass, which cast them upon the radiometer vanes. The vanes were shaded alternately by a brass strip lying on the quartz plate. Deflections were observed on a scale at 1.3 m.

The radiometer case was evacuated with a mechanical air pump for several hours. Then hydrogen was introduced to 0.23 mm. mercury pressure. In a later experiment the hydrogen pressure was doubled. The time of single swing of system, as overdamped, ranged from 10 seconds in vacuum to about 15 seconds in hydrogen. Under these conditions deflections were observed, counting the combined effect from one vane to the other. One of the vanes appeared about twice as sensitive as the other, probably owing to differences in the gas spaces of the double-deck vanes.

In:	Vacuum	Hydrogen, 0.23 mm.	Hydrogen, 0.46 mm.
Deflection:	9 cm.	23 cm.	27 cm.

It is believed that a pressure between 0.23 mm. and 0.46 mm. would be best, and would correspond to a deflection of about 30 cm. Assuming this figure, we make the following comparison with the instrument used by Abbot in 1928, first increasing his reported deflection from 80 to 100 mm. because, as he says, the candle image was not fully intercepted by his vanes.

Relative sensitiveness, 1945 to 1928........ $\frac{300}{100} \times \frac{40}{130} \times \left(\frac{4.0}{2.4}\right)^2 \times \frac{3.7}{0.6} = 19.1$

Assuming that the scale could be removed to 10 m. (for the spot is very bright, and the steadiness excellent) and that deflections of 0.1 mm. could be verified as the mean of several repetitions, and read with the special scale employed in 1928, then a candle flame shining on these tiny vanes could be observed (except for absorption in the atmosphere) at a distance of 1,900 feet.

For the purpose of observing the energy spectra of white and blue stars, other very great advantages are proposed to be utilized over those of 1928. At that time there were 8 silver-on-glass reflections, and a very large flint-glass prism, thus combining, by imperfect reflection, considerable absorption, and unnecessary dispersion to weaken greatly the energy of short wave lengths. It is now proposed to use a very bright special grating, and 7 aluminum-on-glass reflections including the grating. By reference to pages 51, 52, and 105 of volume 2 of the Annals of the Astrophysical Observatory, we find that, as between wave lengths 3900 and 8000 A., the proposed optical train will be about 60 times more efficient than that of 1928. This advantage, together with twentyfold increase of sensitiveness, should combine to insure large deflections and good results on stellar-energy spectra of short wave length.