PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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The Celescope survey and the galactic distribution of interstellar absorption

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The Celescope experiment consisted of four 31 cm aperture telescopes equipped with digital television photometers, installed in the Orbiting Astronomical Observatory, launched 7 December 1968. We used this instrument to conduct a survey in four ultraviolet colours: U1 (2100–3200 Å), U2 (1550–3200 Å), U3 (1350–2150 Å) and U4 (1050–2150 Å). We have published the observational results in the *Celescope catalog of ultraviolet stellar observations* (Davis, Deutschman & Haramundanis 1973).

I have studied these results, together with relevant ground-based data, to determine the distribution of interstellar dust and variations of the interstellar extinction law with the position in the galaxy. Results from the data contained in the Celescope catalogue have been prepared for publication (Peytremann & Davis 1974). These results have now been refined and expanded to include new ground-based U, B, V, and Hβ photometry acquired at Kitt Peak National Observatory, as well as new observations by W. A. Deutschman and R. Schild at Cerro Tololo Inter-American Observatory.

1. Introduction

Short-wave electromagnetic radiation reacts strongly with matter. At wavelengths longer than 3200 Å, the effects of the Earth's atmosphere can be rather well eliminated from observational data by proper reduction procedure. The interaction of short-wave ultraviolet radiation with ozone and oxygen in our atmosphere is so strong, however, that no appreciable amount of radiation of wavelength shorter than 2800 Å penetrates below an altitude of 30 km, and no appreciable amount of radiation of wavelength shorter than 2000 Å penetrates below 100 km.

Far beyond the planets and Sun of our Solar System lie the stars of our Milky Way galaxy. The Milky Way is a highly flattened disk of stars, gas, and dust surrounded by a nearly spherical halo consisting mainly of very old, rather faint stars. The Sun lies near the centre of the disk. The dust, gas, and young stars are distributed rather irregularly in the disk, in the same type of general spiral pattern as seen in many other galaxies in the Universe. Visible light, and ultraviolet light of wavelengths longer than 912 Å, can penetrate only a few thousand parsecs through the general galactic dust layer and less than 100 pc through the densest dust clouds. Ultraviolet light of wavelengths shorter than 912 Å interacts so strongly with the interstellar hydrogen gas that we are able to receive no light of these very short wavelengths from beyond the Solar System. Thus, the field of ultraviolet astronomy, as understood by this conference, deals primarily with electromagnetic radiation of wavelengths between 912 and 3200 Å originating in objects beyond our own Solar System. And the only objects that appear reasonably bright at these wavelengths, as seen from a satellite in orbit near the Earth, are the hot, young stars located mostly in and near the spiral arms of the Milky Way.

The Smithsonian Astrophysical Observatory developed the Celescope experiment to survey the sky in roughly this ultraviolet wavelength range. Since this instrumentation has been discussed in detail elsewhere (Davis *et al.* 1972), I will here only summarize its most important characteristics.

The Orbiting Astronomical Observatory (OAO-2), containing the Celescope experiment, was launched on 7 December 1968 into a nearly circular orbit, 800 km above the Earth's surface, with a 35° inclination. The OAO allowed us to point the Celescope photometers in the desired direction to an accuracy of 1′ with a stability of 15″. We shared space and observing time on OAO-2 with one other experiment, the University of Wisconsin Experiment Package.

The Celescope consisted of two major integrated units: the optical package and the bay E-4 electronic module assembly. The Celescope optical package consisted of four 31 cm Schwarzschild telescopes, each of them imaging a star field on to the ultraviolet-sensitive photocathode of a television image tube (Uvicon). Figure 1 shows how these telescopes and the electronic system were mounted.

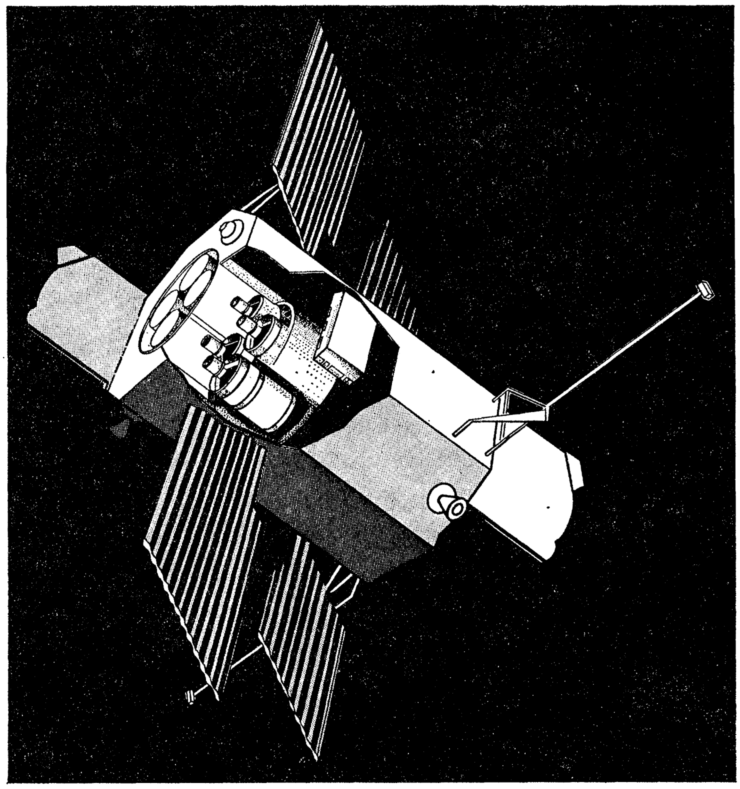

FIGURE 1. OAO spacecraft with cutaway showing the Celescope experiment.

By using an appropriate combination of optical window materials and photocathode materials, we obtained four different spectral response curves, illustrated in figure 2. The television signals from these photometers were digitally encoded by the bay E-4 electronic package and transmitted, via the OAO satellite and a series of National Aeronautics and Space Administration ground stations, computers, and magnetic tapes, to our computing centre in Cambridge, Massachusetts. Each picture represented an area 2.8° × 2.8° in the sky. We used our computer to determine ultraviolet brightnesses and identifications for the stars contained in these pictures, resulting in the *Celescope catalog of ultraviolet stellar observations* (Davis, Deutschman & Haramundanis 1973), on which this paper is primarily based.

Figure 3 shows the distribution, in galactic coordinates, of the pictures taken by Celescope. Most of the high-latitude exposures were obtained during our second month of operation to determine if an appreciable number of galaxies or stars in our own galactic halo were bright in the ultraviolet. We soon determined that none of these galaxies was bright enough in the ultraviolet to be observed by Celescope. Since we found very few stars more than 20° from the galactic plane, we spent our remaining 14 months of observing time concentrating on galactic observations.

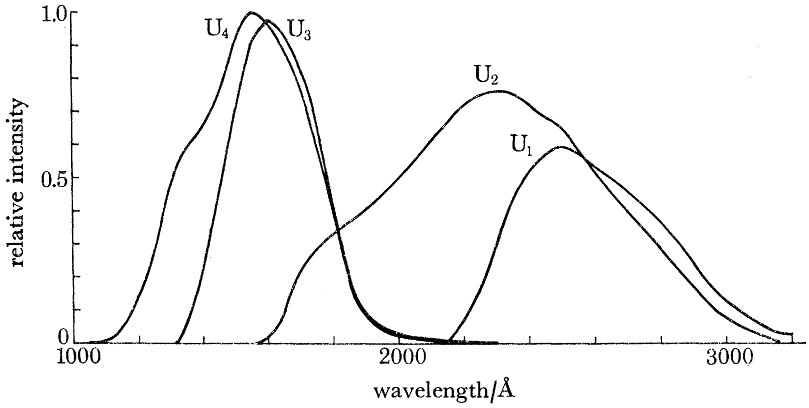

FIGURE 2. Relative spectral response of the filters.

Figure 4 is illustrative of the type of pictures provided by Celescope. The left-hand frame was provided by camera 1, sensitive to U2 in the upper half and U1 in the lower half. The right-hand frame was provided by camera 4, sensitive to U4 in the upper half and U3 in the lower half. This field is the Sword of Orion, with the Orion Nebula (containing the bright star Theta Orionis) near the centre of the picture. Pictorial representations such as these were used only for identifying the objects observed; the brightnesses were always determined by computer analysis of the video data.

In addition to the identifications and ultraviolet magnitudes, the Celescope catalogue contains a summary of important ground-based information for each star obtained from the scientific literature through August 1972. This information includes, where available, photoelectric observations in the UBV system (wavelengths between 3000 and 6600 Å; see Johnson & Morgan 1953) and spectral types in the MKK system (Morgan, Keenan & Kellman 1943). W. A. Deutschman, R. Schild and I have recently completed a new ground-based observing program, using telescopes and photometers of the Kitt Peak National Observatory in Arizona and the Cerro Tololo Inter-American Observatory in Chile to obtain additional photoelectric observations in both the UBV system and the Hβ system (Crawford 1958). We have also added results from more recently published ground-based observations to our data base. This paper is derived from this new expanded data base, including UBV observational material for 85 % of the Celescope stars, Hβ observational material for 58 %, and MKK spectral types for 32 %.

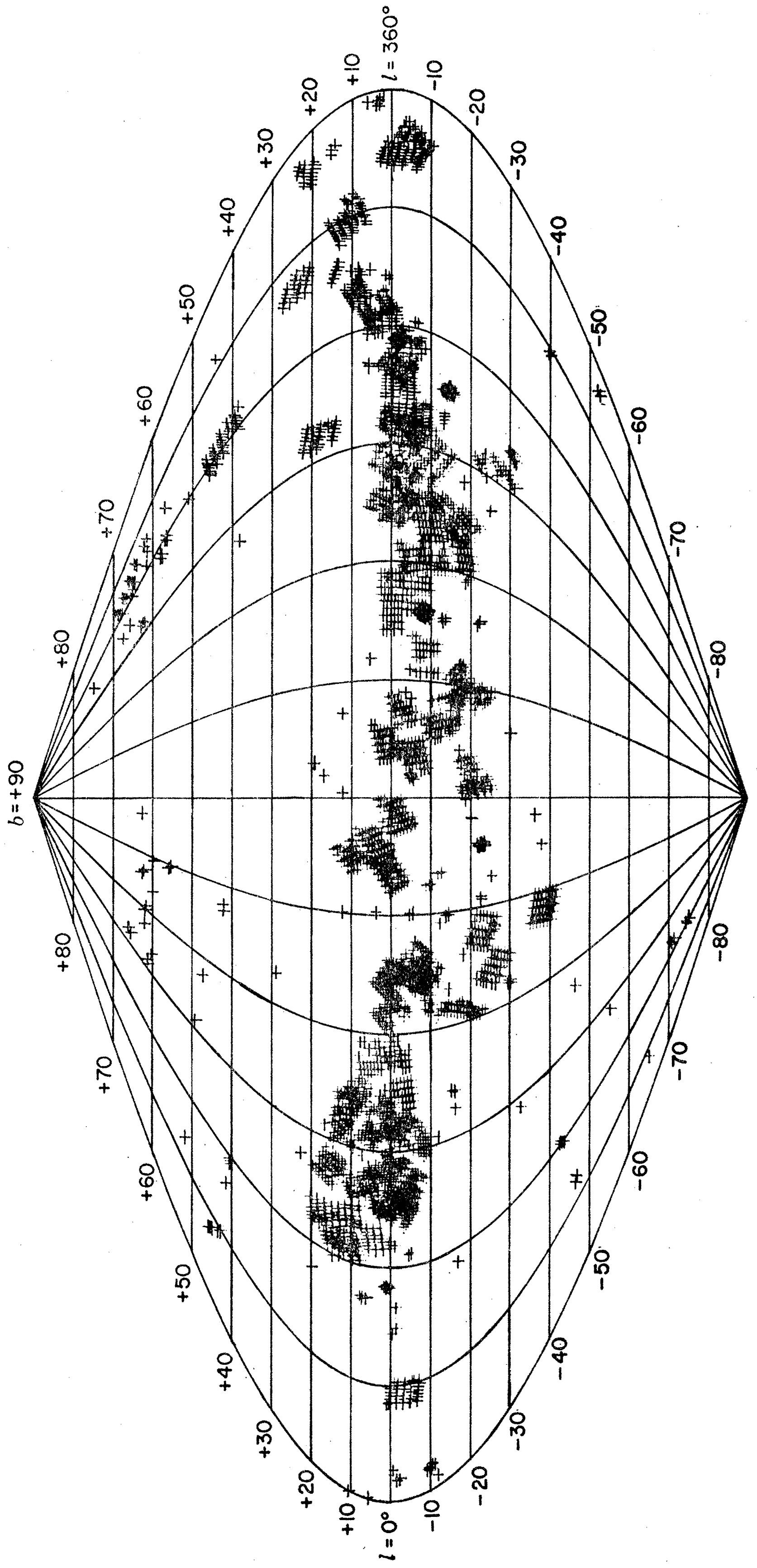

FIGURE 3. Plot in galactic coordinates of the exposures taken by Celescope.

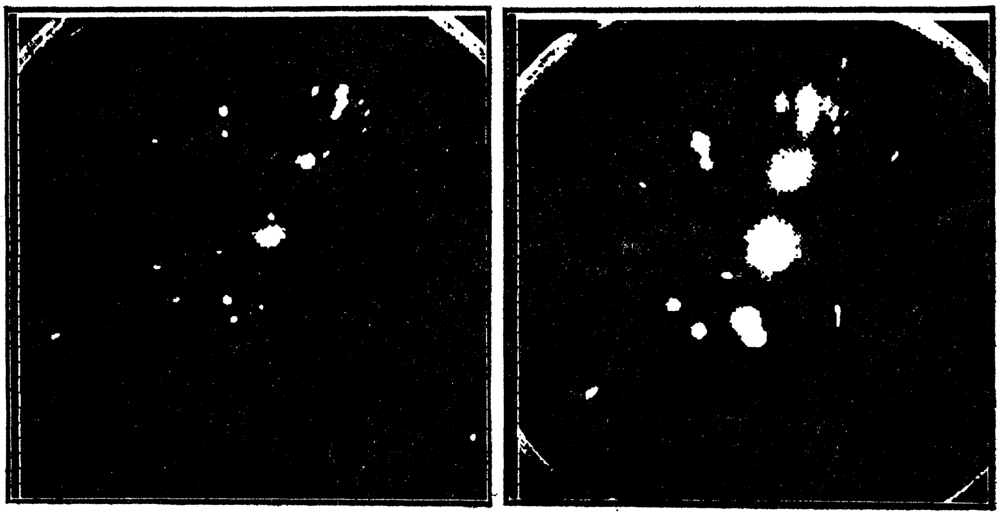

FIGURE 4. Celescope pictures in the region of the Orion Nebula.

2. INTRINSIC PROPERTIES OF STARS

Most stars exhibit an absorption-line spectrum in the so-called 'visible' region (roughly 3200–6000 Å) that can be rather accurately described by a two-parameter system of spectral classification. The classification that has been most commonly used in recent years is the MKK system, named after its originators (Morgan *et al.* 1943). In this system, a letter–number combination (called the spectral type) is one of the parameters; spectral type correlates closely with the effective surface temperature of the star. The other parameter, luminosity class, is designated by a Roman numeral; as its name implies, luminosity class is indicative of the total intrinsic luminosity of the star, which in turn depends on the surface gravity.

The colour of a star, as measured by the difference in its brightness in a pair of broad-band wavelength regions, is also closely correlated with its temperature and, therefore, with its spectral type. The UBV photometric system allows determination of two colours: U-B and B-V are normally used. If we select stars of a single spectral type – for instance, type O9V – and plot E_{U-B} against E_{B-V} for a large number of such stars, we find a very large range of observed colours, with the property that the plotted points imply a nearly linear relation between E_{U-B} and E_{B-V}, as illustrated in figure 5. Similar relations are found for the observed colours of stars of other spectral types: figure 5 also indicates the observed relation for types B3V and B9V. This apparent range of colours for stars of a given spectral type is caused by selective extinction arising from solid particles ('interstellar dust') lying between us and the stars. The distribution and the ultraviolet absorbing properties of this dust – the main subject of this paper – are discussed more fully in §3.

Several techniques are available for removing the effects of interstellar extinction from the observed data in order to obtain intrinsic colours. The one we have used in this research is also illustrated by figure 5. For a particular luminosity class, the stars lie along a well defined colour–colour sequence, indicated for luminosity class V by the dashed line of figure 5. We can determine the intrinsic properties of a star by 'dereddening' it along a line of slope 0.72 in E_{B-V} against E_{U-B}; the dotted line indicates this process for a star having $E_{B-V} = 0.4$,

$E_{U-B} = -0.1$. We use a similar process, described more fully in §3, to determine the intrinsic ultraviolet properties of the stars in the Celescope catalogue.

Stars of luminosity class V are said to lie on the main sequence. These stars generate their energy by conversion of hydrogen into helium. The structure of such a star will depend on its initial mass, its initial composition, its initial angular momentum, its age, and whether it has evolved as an individual star or as a member of a close binary system. For our purposes here, the most important of these properties is the mass. Only stars appreciably more massive than

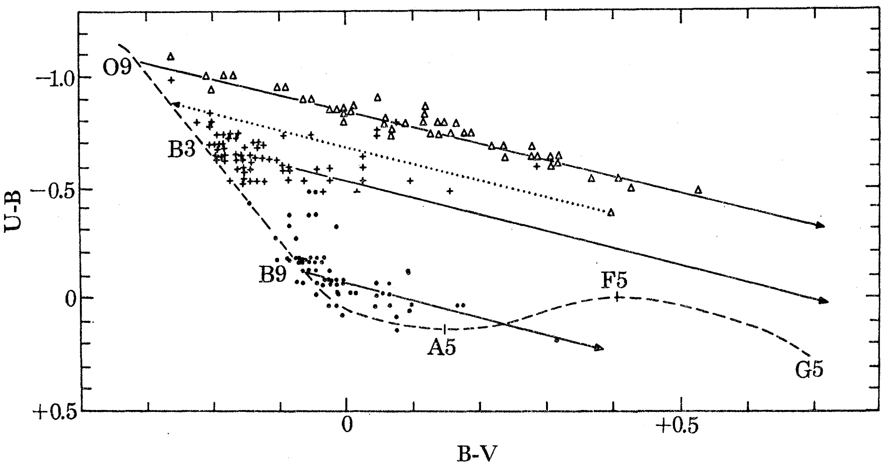

Figure 5. The UBV colour–colour diagram for the main sequence (luminosity class V) and the effects of interstellar reddening.

the Sun emit enough ultraviolet radiation for adequate study by Celescope. And since the lifetimes of such stars are considerably less than the age of the Solar System, they all have a composition similar to that of the interstellar gas and dust from which they have been formed. (The oldest stars known – presumably formed soon after the Galaxy itself – have much less carbon, oxygen, nitrogen, and other heavy elements than the Sun and most other nearby stars.) As a star ages, its atmosphere expands and it becomes brighter; by the time its hydrogen fuel is exhausted, it has reached luminosity class III.

The spectrum of a star depends almost entirely on the structure and composition of its atmosphere. Our understanding of stellar atmospheres is clarified by building mathematical models, most commonly specified by effective temperature (T_{eff}), surface gravity (g) and composition. The predictions of these models are then compared with the observational material in order to improve our understanding both of the stars and of the observational and computational techniques that can be used to study them.

Figure 6 is a comparison of relevant Celescope data with some corresponding theoretical model atmospheres. For stars hotter than 10000 K of luminosity classes V, IV and III, the agreement between predicted and observed colours is quite good. For the A stars (temperatures between 7000 and 10000 K) the U3-V colours predicted by the models of Kurucz, Peytremann & Avrett (1973) are too bright (by about 1 magnitude at 8500 K) and the U2-V colours are too faint (by about 0.25 magnitudes), which implies sources of line opacity in the far ultraviolet in addition to those used in the computations. More detailed comparisons of the Celescope results with predictions from model atmospheres are presented elsewhere (Peytremann & Davis 1974).

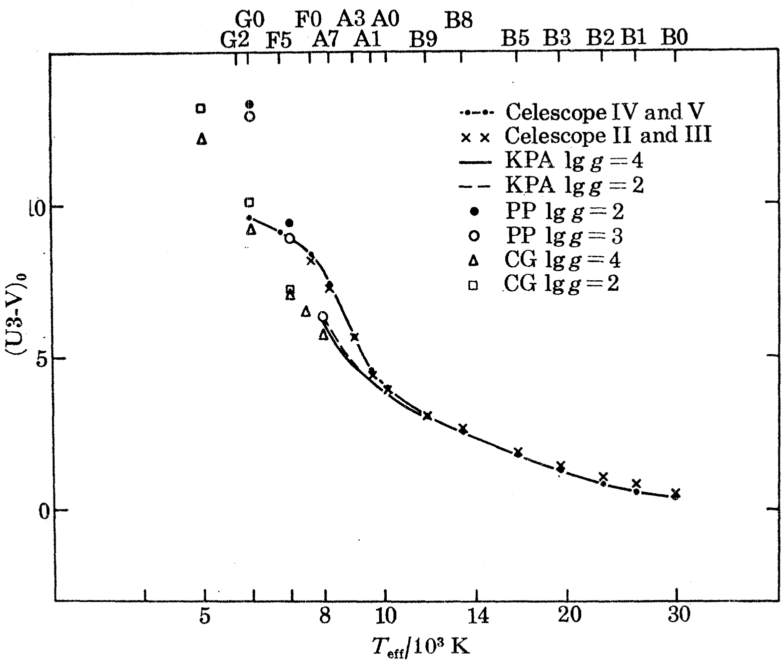

FIGURE 6. Intrinsic U3-V colours, $(U3\text{-}V)_0$, against effective temperature, T_{eff} (lower horizontal axis), and spectral type (upper axis). KPA refers to models by Kurucz, Peytremann & Avrett (1973), PP to models by Parsons & Peytremann (1973), and CG to models by Carbon & Gingerich (1969).

3. INTERSTELLAR EXTINCTION

As mentioned in §1, most of the stars observed by Celescope are hot, young stars lying near the plane of the Milky Way. Such stars are still being formed from the clouds of gas and dust that are found to be irregularly distributed in the disk of the Galaxy in the same general type of spiral pattern that we see in many other galaxies. This dust dims the light of the stars beyond it; the shorter wavelengths are dimmed more than the longer, making the more distant stars appear redder.

As was shown in figure 5, the total amount of reddening in B-V – termed the 'colour excess', $E_{B\text{-}V}$ – can be determined by knowing either the U-B colour or the spectrum, provided the slope of the reddening line is always the same. We have determined B-V colour excesses for the stars observed by Celescope on the assumption that $E_{U\text{-}B}/E_{B\text{-}V} = 0.72$, using only single stars that have no known spectral peculiarities. We then determine ultraviolet colour–colour sequences for these stars, primarily by plotting U2-V against B-V and U3-V against B-V for unreddened stars. Finally, we compare the observed ultraviolet colours for reddened stars against these normal sequences to determine ultraviolet reddening. For each star observed, we can then determine two new parameters: $X2 = E_{U2\text{-}V}/E_{B\text{-}V}$ and $X3 = E_{U3\text{-}V}/E_{B\text{-}V}$. In figure 7, I have plotted $X2$ and $X3$ against galactic longitude for those stars having $E_{B\text{-}V} \geqslant 0.3$, illustrating several important properties of the interstellar dust. First, the extinction ratios $X2$ and $X3$ show considerable scatter, indicating variations in the composition, structure, or alinement of the dust particles in different parts of the sky. Secondly, the extinction ratio $X3$ shows an appreciable correlation with galactic longitude, whereas $X2$ does not. And thirdly, the average values of these extinction ratios are $X2 = 3.6$ and $X3 = 5.0$.

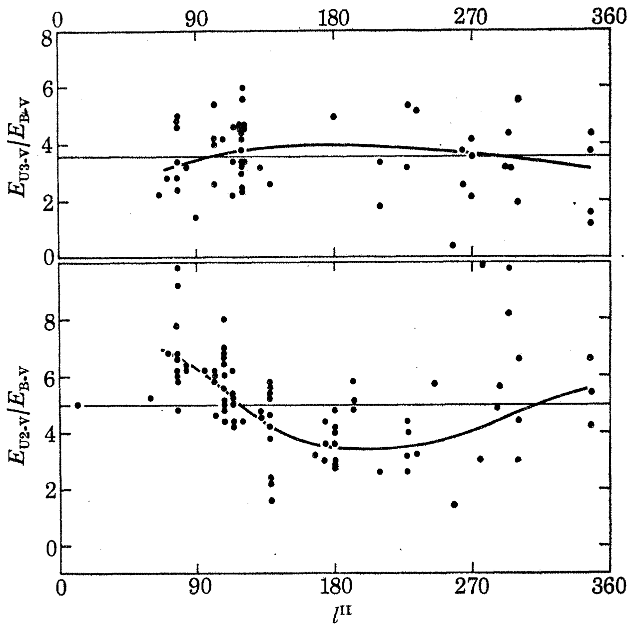

FIGURE 7. Normalized colour excesses, E_{U2-V}/E_{B-V} and E_{U3-V}/E_{B-V} against galactic longitude l^{II} for stars having $E(B-V) \geqslant 0.3$.

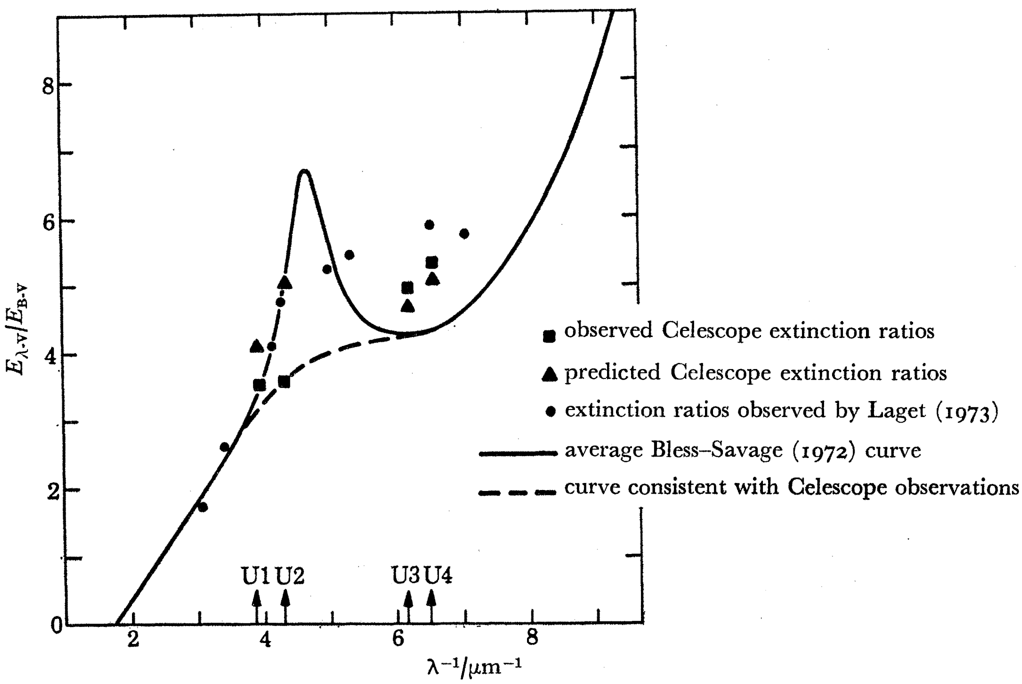

FIGURE 8. Observed extinction ratios, $E_{\lambda-V}/E_{B-V}$ against inverse wavelength $1/\lambda$. The average wavelengths of the Celescope filters are indicated by vertical arrows.

We will return to these properties and to figure 7 shortly. But let us first look at figure 8, which compares out broad-band results ($X2$ and $X3$) with the narrow-band extinction curve published by Bless & Savage (1972). The solid curve represents the extinction as derived from spectrophotometry. The intermediate-band filter photometry by Laget (1973) is, in general, consistent with this curve, whereas the Celescope results are more compatible with the dashed curve. $X3$ agrees with the Bless–Savage results, whereas $X2$ does not. Because many different narrow-band investigations have reached conclusions quite similar to those used in figure 8, it would be tempting to consider the Celescope conclusions a result of calibration problems in the U2 range. Having looked carefully at several possible calibration problems in U2, we conclude that the Celescope calibration is essentially correct except for about 20 of the very brightest stars, all of which are essentially unreddened and do not affect our conclusions. We offer the alternative explanation that the depth of the extinction maximum near 2200 Å is different for interstellar clouds than for the general intercloud medium and that the Celescope results are more strongly dependent on stars that are not obscured by the denser clouds. We are currently using the more complete ground-based photometric data recently obtained at Kitt Peak National Observatory and at Cerro Tololo Inter-American Observatory to investigate in more detail the dependence of the reddening law on the density of the obscuring matter, and variations of both the density and extinction law with position in the Galaxy. Since most of the stars lying behind the denser interstellar clouds were so heavily reddened that they became unobservable by Celescope, interpretation of the Celescope data must take into account an important selection effect: our data are in general more applicable to the intercloud medium than to the denser clouds of interstellar dust. Celescope observed roughly equal numbers of stars at distances between 200 and 500 pc and between 500 and 3000 pc. And because of the selection effect caused by the irregular distribution of interstellar dust, these two groups of stars have similar amounts of interstellar reddening. We have not yet completed our analysis of these results sufficiently to make a definitive statement regarding differences in the properties, other than cloud density, that cause the stars to be separated into these two groups.

I would like to thank Drs W. A. Deutschman, E. Peytremann and R. Schild for many helpful discussions of this material before my presentation at the Royal Society discussion meeting on ultraviolet astronomy. Much of the research reported here is being published in more detail elsewhere in collaboration with them as co-authors.

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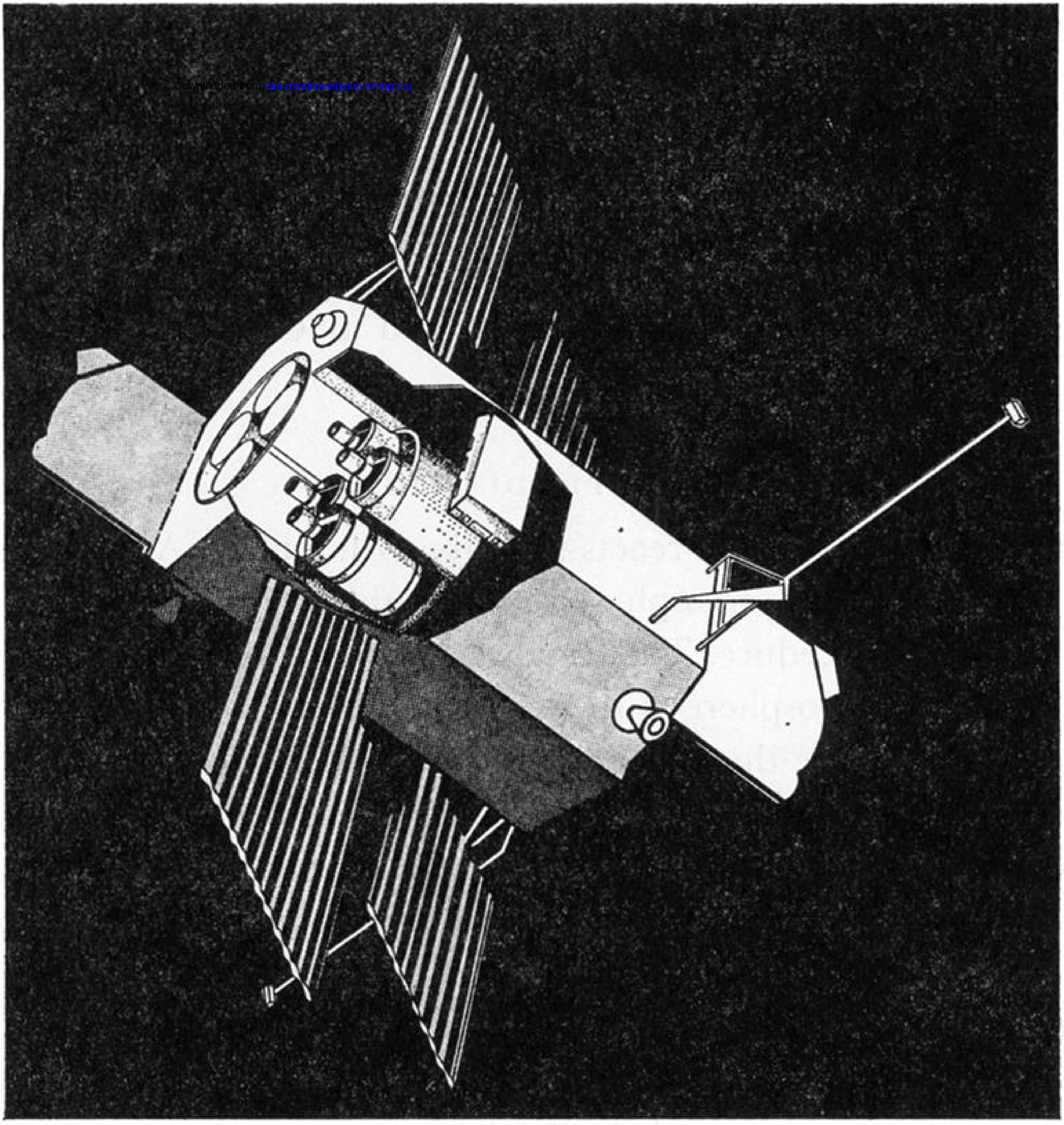

FIGURE 1. OAO spacecraft with cutaway showing the Celescope experiment.