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APPENDIX III

A REVIEW OF SCIENTIFIC RESULTS FROM OAO-2

A. D. Code, B. D. Savage

Introduction

The Orbiting Astronomical Observatory-2 (OAO-2) has been successfully carrying out astronomical investigations in the ultraviolet since launch on December 7, 1968. Earlier reviews of preliminary data analysis have been presented in 04.061.031; 02.113.027; 02.113.033; 06.013.009. In this discussion, data obtained with the University of Wisconsin photometric instruments are presented. The discussions are primarily concerned with data analysis involving University of Wisconsin astronomers. Numerous results obtained by OAO guest investigators can be found in the Proceedings of The OAO Symposium (1) held in Amherst, Massachusetts, August 22–23, 1971.

The OAO spacecraft, operating above the ultraviolet absorbing layers of the earth's atmosphere, provides the capability of pointing telescopes to approximately one minute of arc in the direction of any selected celestial object and maintaining that pointing to approximately one second of arc. In addition, the spacecraft provides command and data links with the ground control stations. It is in every sense a versatile astronomical space observatory. The observatory contains instrument packages from the University of Wisconsin and from the Smithsonian Astrophysical Observatory.

The Wisconsin equipment consists of five telescopes employing photoelectric filter photometers over the spectral region from approximately 1200 Å to 4000 Å, and two objective grating scanning spectrophotometers. The spectrophotometers provide a spectral resolution of about 10 Å from 1100 Å to 2000 Å and 20 Å resolution in the region from 2000 Å to 4000 Å. The photometric accuracy and long term stability of most of these instruments has been exceptionally good. Details of instrumental operation and reliability can be found in Code *et al.* (04.113.017).

One of the major objectives of OAO-2 was to determine the spectral energy distributions of stars in the ultraviolet. Ultraviolet magnitudes for a large number of stars of diverse types are provided by the OAO filter photometers. Such information will provide basic data for determinations of stellar effective temperatures, bolometric corrections, chemical composition, and inter-stellar extinction. This information will ultimately be provided in the form of a catalog of ultraviolet magnitudes. Note the very large range of ultraviolet magnitudes for stars of different types. The $(1700-V)_0$ color changes approximately 10 magnitudes for every 1 magnitude change in $(B-V)_0$ color. Since the photometric accuracy of the OAO-2 ultraviolet measurements is comparable to that of the $B-V$ determinations, the ultraviolet color provides a much more sensitive measurement of the

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differences among stars. It is apparent that there are no large systematic effects due to luminosity classes or to rotation among the stars plotted. If metallic line stars were included they would fall below the relation exhibited here for 'normal' stars.

For brighter stars, more detailed information on spectral energy distributions is provided by the scanning spectrometer. This spectrum was obtained by combining digital counts from four independent scans, each made with the normal stepping interval of 10 Å between data points but displaced 2·5 Å for each successive scan. The agreement between these independent scans is typical of the repeatability and stability of this spectrometer, which has shown no significant degradation over a three-year period. The strongest absorption lines in this spectral region for early-type stars are the Lyman alpha line at 1216 Å and the resonance lines of Si IV and C IV at 1400 Å, and 1550 Å, respectively. The Lyman alpha line in δ Sco is primarily due to interstellar atomic hydrogen. The correct stellar energy distribution can be recovered by dividing the digital counts by the known instrumental sensitivity function determined from preflight calibrations and recent, calibrated measurements of selected stars from rockets. Spectral energy distributions based on spectrometer measurements are being derived for approximately 150 stars to supplement the filter photometry data. The rocket calibration flights utilized photometers carefully calibrated with ultraviolet synchrotron radiation from a laboratory source and should enable us to provide ultraviolet energy distributions to an accuracy of 5 to 10%.

In the following sections we describe the results of some of the investigations currently being carried out with OAO data. These studies range from solar system objects to extragalactic systems and indicate the types of investigation that can be conducted with this first stellar space observatory.

Ultraviolet observations of comets

The first observations of a comet in the vacuum ultraviolet occurred on January 14, 1970, when OAO-2 recorded the ultraviolet spectrum of comet Tago-Sato-Kosaka (1969 g) (03.103.101; 04.103.103; (**1**), p. 109). Spectrophotometric measurements of this comet were continued throughout January of that year. The observations revealed, among other things, the extensive hydrogen Lyman alpha halo first predicted by Biermann and Trefftz (**2**). On January 28, Princeton University astronomers obtained a photograph of the nucleus in Lyman alpha revealing finer scale structures of the nucleus (**3**). In February of 1970, the bright comet Bennet (1969 i) became observable. On the basis of the OAO discovery, OGO-V made several measurements of the comet with low spatial resolution instruments capable of following the hydrogen halo out to fainter isophotes (03.103.102). OAO-2, however, was able to continue systematic observations both at Lyman alpha and in other spectral regions to follow the temporal changes in the comet's brightness.

A variety of circumstantial arguments suggested that among the cometary ices, water ice was the most abundant and that the evaporation of water could account for the comet coma. The subsequent photodisassociation of water should yield primarily atomic hydrogen and OH with smaller amounts of O I and H_2. However, until the OAO observations, only OH among these products had been detected and because of the strong atmospheric absorption at 3090 Å and the low *f* number, accurate intensities, isophotes, and variations with solar distance of the OH emission were not known. The OAO measurements provide data on the distribution and temporal variations of OH, H and O I and establish an upper limit to the H_2 abundance. Features due to H I (1216 Å), O I (1302 Å), OH (2860 Å, 3090 Å), NH (3360 Å), and CN (3580 Å, 3883 Å) are identified in spectrum of Comet 1969 i. Since the OAO scanners are objective grating spectrometers the line profiles are related to the spatial distribution of the emissions. One minute of arc corresponds to 5 Å. The full width at half intensity of the Lyman alpha emission line corresponds to an angular size of 26 min for the hydrogen halo. This is slightly smaller than the angular diameter of the sun. The great abundance of OH is indicated by the greater intensity of the OH band at 3090 Å compared by the strong CN band at 3883 Å. The OH emission is about 3 times as strong as the CN, despite the fact that the solar spectrum is 3 times as intense in the region of the CN band and the *f* number for CN is about 24 times as great. Thus OH is more than 200 times as abundant. From the Lyman alpha isophotes of the extensive hydrogen halo the number density of hydrogen atoms can be derived; the total area corresponds to some 10^{12} grams of hydrogen, while the profile implies the emission of approximately 10^{29} molecules of H_2O per second per steradian. This result is consistent with the measured isophotes of OH and suggests a lifetime for the OH radical of the order of 2×10^5 seconds. The hydrogen halo is found to be optically thick out to distances of the order of 10^5 km. The line width is approximately 10% of the solar Lyman alpha line width and the observed surface brightness in the central 10 minutes of arc is essentially the same as the calculated reflected sunlight over this line width.

Another source of valuable information on the nature of comet structure is provided by the variation of surface brightness with heliocentric distance. Both H and OH display the same dependence on distance, varying approximately as the inverse 6th power. Delsemme (05.102.025) interprets this result to imply a three-step process for both the H and the hydroxyl halo, where each step follows approximately an inverse square law dependence. Since virtually all the H_2O would be dissociated within the halo the inverse square dependence of dissociation should not affect the observed surface brightness. The interpretation of these observations is therefore probably more complex than that described by Delsemme.

In the case of comet Tago-Sato-Kosaka, observations were carried out through perigee. This provided the opportunity to measure the width of the comet Lyman alpha emission line by following the effects of the narrow absorption due to the earth's geocorona as it moved across the comet line with the changing Doppler shift. If the Lyman alpha emission profile of the comet is Gaussian, then the Doppler width corresponds to a temperature of 1600 K.

Comet 1969 g was observed during the time in which its coma occulted the star π Psc and comet 1969 i when it occulted σ Cas. Preliminary analysis of these data indicates absorption of starlight in the center of the OH band for comet 1969 g.

Ultraviolet observations of the planets

OAO planet observations are being analyzed by a group of guest investigators and Wisconsin astronomers. The satellite has obtained ultraviolet data on Venus, Mars, Jupiter, Saturn, Uranus, and Neptune. For Venus, Mars, Jupiter, and Saturn the data consist of spectral scans (resolution ~ 20 Å) over the regions 3000–2000 Å and photometry at bands centered at 4200 Å, 3300 Å, 3000 Å, 2500 Å, 2000 Å, and 1500 Å. In the case of the faint planets, Uranus and Neptune, the data consists of photometry at 4200 Å, 3300 Å, 3000 Å, and 2500 Å. No planets have been detected with the short wavelength spectrometer in the region 1050–1900 Å. Ultraviolet planetary observations are important because, at the shorter wavelengths, the effects of molecular scattering become more and more important relative to scattering from cloud particles or planetary surfaces. In addition, many molecules and atoms have resonance lines in the ultraviolet so that more precise limits can be set on the presence or absence of a large number of interesting molecules.

Determining the albedo or reflectivity as a function of wavelength is basic to the study of planetary atmospheres. For this purpose we need accurate solar spectral energy distributions. Although a number of ultraviolet observations of the sun have been made, most of these data are unsuitable for determining accurate ultraviolet planetary albedos (03.093.015). In the case of near-ultraviolet ground-based observations of the planets, this difficulty has been overcome by comparing planetary spectra to observations of solar-like stars made with the same instrument. This method has the advantage that one does not need to know the instrumental sensitivity curve. OAO has obtained good scans for stars similar to the sun for wavelengths longer than about 2700 Å.

A new OAO ultraviolet albedo curve for Jupiter is given in (**4**). This curve was obtained by using stellar data down to 2700 Å and a new photoelectric spectrum of the sun by Broadfoot at shorter wavelengths. There is a good agreement between the OAO data and the ground-based data in the region of overlap, (05.099.026; and **5**). The albedo curve for Jupiter shows a rise toward shorter wavelengths which is probably due to Rayleigh scattering from molecular hydrogen. At $\lambda \lesssim 2300$ Å, the albedo rapidly drops, indicating an increase in absorption which is most likely due to gaseous ammonia. The detailed explanation of this albedo curve will undoubtedly involve scattering from both molecules and cloud particles. The actual albedo will depend in a complicated way on the nature of the cloud particles and their spatial distribution relative to the gaseous constituents of the atmosphere.

It has been possible to search carefully for new narrow absorption features in the OAO planetary data by intercomparing spectral scans of one planet with those of another (**4**). In the case of the planets Mars, Jupiter, and Saturn no new narrow absorptions have been found. An upper limit of about 3 Å equivalent width can be set for the region 2100 Å to 3200 Å. These upper limits have been used to derive upper limits for a large number of possible molecular constituents in the atmospheres of Saturn, Mars, and Jupiter (**1**, p. 139).

The preliminary albedo curves discussed by Wallace (04.097.011) indicated that an average column density of 2×10^{-4} cm atm of O_3 may be present in the atmosphere of Mars. However, those preliminary curves were entirely based on an uncertain solar spectrum. Recent work by Caldwell (**6**) has shown that the broad feature identified as O_3 by Wallace (04.097.011) was likely introduced by uncertainties in the solar spectrum .A detailed analysis of Mars' albedo curve was made by Caldwell (**7**). He concluded that the albedo could be matched by invoking Rayleigh scattering from the known amount of atmospheric CO_2 (80 m-atm) plus a slowly decreasing ground albedo toward shorter wavelengths. The derived ground albedo disagrees with reflectivities expected for a number of suggested ground materials.

OAO observations of interstellar dust

OAO can provide valuable new information on the scattering characteristics of the interstellar dust. Observations of diffuse galactic light can be used to obtain information on the ultraviolet albedo and phase function of the dust while observations of reddened stars can be used to derive the extinction characteristics of the dust. Here we will discuss the OAO extinction data. Of the approximately 300 O- and B-type stars OAO has so far observed (up to February 1972), about 75 are suitable for deriving interstellar extinction curves (**8**). The curves were obtained by intercomparing reddened and unreddened stars of the same spectral type and when possible the same luminosity class. The general characteristics of these curves are: (1) all extinction curves have a pronounced bump, which in most cases peaks at 2175 Å $\pm$ 25 Å; (2) all extinction curves have a broad minimum somewhere in the region 1800 Å to 1300 Å; (3) all curves show a rapid rise in extinction toward the far ultraviolet; (4) there are significant variations in ultraviolet extinction, the variations being greatest in the far ultraviolet.

While a satisfactory detailed interpretation of the OAO extinction curves does not yet exist, a large number of theoretical suggestions have already emerged. For example, Stocher (02.131.027), Gilra (05.131.086) (05.131.045) believe graphite particles may be responsible for the pronounced bump; Huffman and Stapp (05.131.044) attribute the bump to silicates; Manning (05.131.046) suggested quartz; and finally, Graham and Duloy (05.125.035) indicated that solid hydro-carbons could produce the bump. A review of all these suggestions and a discussion of the physics of extinction bumps has been given by Gilra (**1**, p. 295) who concludes that the most likely cause of the bump is plasma oscillations in small (mean radius $\sim$ 100 Å), uncoated, interstellar graphite particles.

The observed variation in the shape of the extinction curves demonstrates that multi-component models of interstellar particles are likely required. This the material responsible for the far ultraviolet extinction is probably different from that producing the extinction at the bump.

OAO observations of diffuse galactic light are being studied by Lillie and Witt (**1**, p. 199). The studies of diffuse light and reflection nebulae together with the extinction data should provide a better understanding of the nature of interstellar particles and are also helpful in understanding ultraviolet radiation from extragalactic systems.

Studies of interstellar Lyman alpha absorption

The short wavelength spectrometer on board OAO has a spectral resolution which is adequate for making measurements of the strong Lyman alpha absorption line at 1216 Å due to interstellar neutral hydrogen. This line has been observed in approximately 70 stars of spectral type B2 or earlier. For stars later than B2 the stellar Lyman alpha line becomes very strong making useful measurements of interstellar absorption difficult. Although radio astronomers have obtained an enormous amount of information on the distribution and kinematics of the neutral hydrogen from 21-cm line studies, the new Lyman alpha absorption data are unique because one can now investigate carefully the relationship between the amounts of interstellar hydrogen and other interstellar constituents such as atoms, molecules, and grains along precisely the same path. Radio observations of 21-cm emission usually average the brightness distribution over a large solid angle (usually about 1° in diameter) and oftern the path length over which the emission occurs is uncertain. Optical measurements of gas and dust and Lyman alpha measurements subtend an infinitesimal sampling area (the projected area of the star). The uncertainty in the path length for the radio data was revealed when the first Lyman alpha absorption data were obtained by the rocket experiments of Morton (**9**). These early observations showed the unexpected result that the hydrogen column density in the directions of δ Ori and ζ Ori was about $1{\cdot}5 \times 10^{20}$ hydrogen atoms/cm^2 corresponding to an average space density of 0·1 atoms/cm^3 instead of the $1{\cdot}3 \times 10^{21}$ atoms/cm^2 or 1 atom/cm^3 derived from 21-cm emission data.

Preliminary results of an analysis of the OAO Lyman alpha data were discussed by Savage and Code (03.012.014). That discussion revealed that the OAO spectral resolution was not adequate to separate the interstellar Lyman alpha from neighboring stellar absorption lines. Due to this line blending, in the preliminary report upper limits to the hydrogen column density as obtained from the OAO data were presented, from which important conclusions were drawn. Since that report an extensive effort has been made by Wisconsin and Princeton University researchers to account for the effects of stellar line blending and to resolve certain disagreements between the rocket data and the OAO data. In a number of cases the OAO upper limits were significantly larger (2 to 3 ×) than published rocket results. Most of these differences have since been attributed to a number of factors, involving both the OAO data and rocket data, such as effects of line blending, placement of the continuum levels, and incorrect allowance for the broad wings of the Lyman alpha line.

Savage and Jenkins (**10**) have shown that it is possible to make reasonably accurate determinations of the H column density from OAO data for about 70 stars. These measurements were made by using the higher resolution rocket data as a guide in determining the amount of line blending in the OAO data. In the case of the star δ Sco the OAO line profile has been compared with a recent observation of the Princeton rocket group. The higher resolution Princeton data has been smoothed to the OAO resolution. Except for a slight difference between the stellar lines on the long wavelength wing of Lyman alpha probably due to residual absorption in the rocket measurements, the agreement is excellent considering that these data were obtained by two totally different methods.

In the paper of Savage and Jenkins (**10**) OAO Lyman alpha column densities were compared with 21-cm emission measurements and a very poor correlation was found. In contrast the OAO column densities correlate, well with Na I and Ca II column densities and $E(B-V)$ measurements. These new data were used to determine the abundance ratios of Na and Ca to H as well as the ratio of mass densities of H to dust in the interstellar medium. The results obtained were: $\langle \mathrm{Na/H} \rangle = 2{\cdot}3 \times 10^{-7}$, $\langle \mathrm{Ca/H} \rangle = 6{\cdot}8 \times 10^{-9}$, and $\langle \varrho_{\mathrm{H\,I}}/\varrho_{\mathrm{dust}} \rangle \approx 100$.

The average space density of hydrogen for all the Lyman alpha stars observed was 0·6 atoms/cm^3. For these stars the average distance was 300 pc. If one only uses stars with distances < 140 pc an average hydrogen space density of 0·25 atoms/cm^3 is obtained. In contrast to the early rocket results which included only a few stars, the average space density of H obtained from the OAO Lyman alpha data does not differ greatly from average space densities derived from 21-cm radio data.

Observations of ultraviolet emission line objects

The OAO has observed ultraviolet emission lines in a number of astronomical Objects (see Table 1

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for a sample list). Ultraviolet emission lines are of great interest for the clues they provide to the structure of extended, often violently moving, stellar atmospheres. In 1967 Morton (**9**) discovered that a few early-type stars in Orion are surrounded by rapidly expanding circumstellar shells. Evidence for these expanding shells came from rocket ultraviolet spectra which showed emission line profiles of the P-Cygni type for the strong ultraviolet resonance doublets of Si IV (1394 Å, 1403 Å) and C IV (1548 Å, 1551 Å). Typical velocities were in the range 1000–2000 km s^{-1}. Such large velocities suggested that the rate of mass loss by these early-type supergiants might significantly influence the evolution of the star. Furthermore, high mass loss rates may significantly disturb the surrounding interstellar medium.

OAO has been used to expand the early rocket observations to a larger number of stars. Even at the relatively low spectral resolution of OAO-2 (full width at half intensity of 12 Å for the short wavelength spectrometer and 25 Å for the long wavelength spectrometer) one can see P-Cygni profiles in certain early-type stars. The high quality data obtained by the OAO makes possible good determinations of the equivalent widths of these strong ultraviolet spectral lines (03.012.014). Finally, the extended lifetime of the OAO has made possible a survey of most bright ($m_v < 5$) early-type

Table 1

A sample listing of some of the ultraviolet emission lines OAO-2 has so far observed. Many more lines may be detected after a more complete analysis of the data. Included in the table are emission lines detected in early-type stars, late-type stars, peculiar stars, novae, and comets.

Object	Spectral type	m_v	Ultraviolet emission lines (λ in Å)
HD 50896	WN5	6·90	N V (1230, 1243), N IV (1496), C IV (1548, 1551), He II (1640), N IV (1718), He II (2740), He II (3203), N IV (3480), plus unidentified lines
γ Vel	WC7	1·82	Si IV (1394, 1403), C IV (1548, 1551), He II (1640), N V (1719), C III (1909), C IV (1923), C III (2298), C IV (2405), C IV (2525).
ζ Pup	O5f	2·25	N V (1239, 1243), C IV (1548, 1551), He II (1640), N IV (1719)
ζ Ori	O9·5 Ib	1·73	Si IV (1394, 1403), C IV (1548, 1551).
α Cam	O9·5 Ia	4·30	Si IV (1394, 1403)
κ Ori	B0·5 Ie	2·06	Si IV (1394, 1403), C IV (1548, 1551).
β Lyr	B9 pc	3·40	L_α (1216), Si IV (1394, 1403), C IV (1548, 1551), Mg II (2796, 2803), plus unidentified lines
α Boo	K2 IIIp	0·06	Mg II (2796, 2803)
ε Peg	K2 Ib	2·40	Mg II (2796, 2803)
α Tau	K5 III	0·86	Mg II (2796, 2803)
β And	M0 III	2·03	Mg II (2796, 2803)
α Sco	M1 Ib	1·08	Mg II (2796, 2803)
α Ori	M2 II-III	0·86	Mg II (2796, 2803)
Nova Ser 1970			Mg II (2796, 2803), plus unidentified lines
Comet 1969 g and Comet 1969 i			L_α (1216), O I (1302), OH (2860), OH (3090), NH (3360), CN (3580), C_3 (3680), CN (3883), C_3 (4000), plus unidentified lines

stars so it will now be possible to determine in what parts of the HR diagram the mass loss phase occurs.

OAO has observed a number of peculiar stars exhibiting emission lines. For example, β Lyr (Table 1) is an eclipsing binary system, one component of which is a hot B-type star. Mass exchange occurs between the two stars, and this gas in the intense radiation field produces a large number of emission lines. OAO has obtained spectral scans and photometry data for β Lyr through the entirety of its 13 day cycle. These data have been released to interested astronomers through the NASA data

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bank. A preliminary interpretation of these data has been given by Kondo, McCluskey, and Houck (**1**, p. 485) which has also generated speculation that one of the components may be a black hole.

OAO has accumulated a large amount of data on cool, late-type stars. Those data consist of both spectral scans (for the brightest late-type stars) and photometry. The value of late-type star observations for the determination of ultraviolet planet albedos has already been discussed. Here we will discuss the ultraviolet emission lines observed in late-type star spectra. A preliminary analysis of the spectral scans by Doherty (06.114.120) lead to the discovery of emission in the Mg II (2796 Å, 2803 Å) doublet in a number of late-type giants and supergiants. In the spectra of α Boo (K2 IIIp) and α Ori (M2 II-III) Mg II is clearly in emission above the adjacent continuum level. A list of late-type stars definitely showing Mg II emission at the OAO resolution of 25 Å appears in Table 1.

Like the Ca II H and K emission cores, the Mg II emission lines in cool stars provide information on the structure of stellar chromospheres. Details of the Mg II profiles cannot be obtained with OAO resolution. However, Doherty (**1**, p. 465) finds that the relative strength of the Mg II emission compared to Ca II emission for eight giants and supergiants is nearly constant and about equal to the relative strength observed in the sun. This result is difficult to understand because one would expect the relative strength of these emission lines to be very sensitive to the run of physical conditions through the chromospheric regions of stars. A possible but unlikely implication of this observation is that the regions of the atmospheres that form Ca II and Mg II emission may be quite similar in all late-type stars. Further theoretical work is needed to fully explore the implication of this observational result.

Although a search has been made for emission lines other than Mg II in late-type stars, none has been definitely detected. However, it is likely that a higher resolution instrument such as the spectrometer in OAO-C will reveal numerous other chromospheric lines, as well as weak emission in the bottom of the Mg II absorption line in most late-type stars.

OAO spectrometers and photometers have observed a number of diffuse nebulae and planetary nebulae. Unfortunately, no emission lines have yet been unambiguously detected in these objects. It appears that more sensitive instrumentation will be required in order to make observations of ultraviolet emission lines in gaseous nebulae. It is possible, however, to study the continuous spectra of nebulae. Holm (**1**, p. 229), for example, has interpreted the continuous ultraviolet spectra of planetary nebulae in terms of Balmer and two photon emission by atomic hydrogen.

Ultraviolet observations of nova serpentis 1970

OAO observations of Nova Serpentis 1970 were obtained throughout the first 60 days following outburst, in February 1970, with both the filter photometers and the long wavelength spectrometer (**1**, p. 535). The spectrum evolved from an absorption line spectrum similar to that of a reddened F star to a strong emission line spectrum over this period. At the spectral resolution of 20 Å, the emission lines first made their appearance about six days after discovery. During this period, while the light was steadily dropping in the visual and photographic, both the underlying continuum and the broad emission features continued to brighten. The visual brightness decreased about 2·5 magnitudes while the flux in the region of the Mg II resonance lines increased by about 1·5 magnitudes. If we attribute this increase of line strength through the first 50 days to an optically thick shell and assume that the optical depth becomes unity where the strength begins to decrease, we may estimate the total number of Mg II ions. The result is consistent with the usual estimates of nova mass loss.

The energy distribution defined by the filter photometry and ground-based data yields approximately constant total flux in the 1000 to 6000 Å interval during the first 60 days, the decrease in light in the visual being due to a shift of the energy curve towards the ultraviolet as the system evolves. These results suggest a model in which the bolometric luminosity remains relatively constant but the conversion of far ultraviolet photons to longer wavelengths undergoes a secular change as the density of the shell decreases. The system is thus somewhat analogous to the rapid evolution of a planetary nebula.

The ultraviolet energy curve as well as $B-V$ color measurements suggest an interstellar visual extinction of the order of one magnitude. It is interesting to note that if this extinction is produved by a nearby dust cloud, then the energy absorbed by the grains is sufficient to account for the infra-red emission commencing about 50 days after outburst and reaching a maximum about 90 days. However, other models for the infrared flux are also suggested by the observations described here.

Ultraviolet photometry of galaxies

To date OAO observations have been reduced for 35 galaxies of diverse morphological type (**1**, p. 559). The measurements were made with the filter photometers utilizing a 10 arc minute diaphragm.

Galaxies are systematically brighter shortward of 2500 Å than stars of similar spectral distribution in the photographic and visual region of the spectrum. The color index m (1920 Å–3330 Å) is arbitrarily set to zero for an F6 V star. For the same $B-V$ colors the galaxies are approximately three magnitudes bluer than main-sequence stars at 1920 Å. Late-type giant stars fall about midway between the galaxies and main-sequence stars. The two Seyfert galaxies, NGC 4051 and NGC 1068 colors do not deviate from those of normal galaxies.

The spectral distributions of spiral galaxies are understandable in terms of the contribution from early-type stars (presumably in the spiral arms) as modified by interstellar absorption. The results for elliptical galaxies, in which the energy distribution appears to rise steeply shortward of 2500 Å cannot be interpreted in terms of early-type stars alone. An infinite-temperature black body would rise with a slope of λ^{-4} while these curves rise as steeply as λ^{-20}. It is difficult to imagine any reasonable source, thermal or non-thermal, that would behave in this manner. It may be significant that the minimum of these curves is near the maximum of our interstellar extinction curve. If it is assumed that elliptical galaxies do contain significant quantities of dust and that the albedos of the particles decrease in the vicinity of the 2200 Å interstellar extinction peak, it is possible to reproduce the observed curves. It would then also be true that a significant fraction of the bolometric luminosity of the galaxy is radiated by these grains in the infrared.

These OAO observations should prove important for furthering our understanding of many problems of extra-galactic astronomy including the stellar luminosity function, interstellar absorption in galaxies, K therm corrections required in photometry of distant, redshifted galaxies, and the magnitude of the extragalactic sky brightness.

Variable stars

Extensive ultraviolet observations have been obtained of variable stars of diverse types (a small sample list is given in Table 2). In the visible part of the spectrum of the magnetic variable α^2 CVn, exhibits spectral variations of line intensities and radial velocities of overabundant rare-earth and and iron-peak elements. Furthermore, with the same period there is a strong magnetic field variation from -4000 to $+5000$ gauss. The most common interpretation given for these variations is that a

Table 2. Sample List of OAO Variable Star Observations

Star	Spectral type	Comments	Period
β Lyr	B5p + ?	Eclipsing variable (β Lyr type)	12·9d
VV Ori	B2 + B8	Eclipsing variable (β Lyr type)	1·48d
CW Cep	B1·5 + B1·5	Eclipsing variable	2·73d
U Oph	B5 + B5	Eclipsing variable (Algol type)	1·68d
RR Lyr	AB	Pulsating variable (RR Lyr type)	0·57d
β Dor	F8 Ia	Pulsating variable (Cepheid variable)	9·84d
β CMa	B1 II	Pulsating variable (β CMa type)	0·25d
β Cep	B1 II	Pulsating variable (β CMa type)	0·19d
α^2 CVn	B9·5 p	Magnetic and spectrum variable	5·47d

magnetic dipole field is inclined to the axis of rotation of a star, and concentrations or patches overabundant in certain elements rotate with the star, producing spectral changes. The OAO light curves for this star indicate that a maximum intensity of the rare-earth lines, the ultraviolet continuum shortward of 2900 Å is greatly diminished while at the same time the visual spectral region becomes brighter. Molnar (**1**, p. 449) has interpreted this as being due to the variable strong line-blanketing by the abundant rare-earth elements.

There are three important features to point out in relation to these measurements of variable stars. First, these observations extend investigations to a previously unexplored spectral region. Thus new phenomena and insights are gained, such as the variations of Lyman alpha in β Lyrae reported by Houck (**1**, p. 479) and its interpretation in terms of gas flow in the system. The second aspect of these observations is that they supplement the classical treatment of variable stars by extending the spectral region covered and by the fact that the observations are often of higher accuracy than ground-based photometry. Finally, the complete coverage in time made possible by an orbiting observatory enables one to obtain complete light curves over a single period with the same instrument for stars for which this could not be accomplished from the ground.

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APPENDIX IV

THE ROCKET ASTRONOMY AT GODDARD SPACE FLIGHT CENTER

A. Boggess

The rocket astronomy program at the Goddard Space Flight Center has concentrated on absolute photometry in the ultraviolet, ultraviolet spectropolarimetry, and ultraviolet stellar spectroscopy. D. C. Evans has obtained photometric flux measurements of α CMa, γ Ori, κ Ori, and α Leo in the range 1150 to 4000 Å. The rocket-borne instrument consisted of a 33-cm diameter telescope, a rotatable concave diffraction grating, and three pulse-counting photomultiplier photometers. The laboratory standards used as photometric references derive their primary calibrations from the United States National Bureau of Standards. An error range of no more than 10 % is attributed to the laboratory standards, with an additional 8 % attributable to the transfer of the calibration to the rocket instrumentation. Random errors contribute another 10 %, resulting in an overall r.m.s. error of about 15 %. Near 3500 Å the data are about 15 % lower than the ground-based photometry of Schild, Peterson, and Oke. Comparison with the provisional calibration of the University of Wisconsin spectrometers in OAO-2 shows good agreement above 2200 Å. From 2200° to 1800 Å, these data produce flux values systematically lower than the OAO-2 calibration by amounts up to 30 %. At shorter wavelengths, there are star-to-star inconsistencies between the rocket and OAO observations.

T. P. Stecher has flown a rocket payload similar to the one described above, but modified by enlarging the spectrometer slits to 50 Å and placing polarizing elements behind these slits. The target star was ζ Ophiuchi O9·5 V, $E_{B-V} = 0{\cdot}32$, $P_v = 0{\cdot}03$, $\theta = 126$. The rocket was programmed to

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point at the star and to roll to the position angle of maximum polarization as observed from the ground. The spectrum was then scanned from λ 1200 and back. The rocket was then rolled through 90° and the spectrum was scanned again. The sequence was repeated for 180° and 270°. The telemetered data was averaged over 50 Å intervals which have a mean error of about 2 %. The preliminary reduction indicates that the polarization is an oscillatory function of nearly constant amplitude with a period that lengthens with frequency.

A. M. Smith has flown rockets to obtain ultraviolet spectra of three stars: ζ Pup (O5f), ζ Ori (O9·5 Ib), and ζ Oph (O9·5 V). The first two stars were observed with a small Wadsworth spectrograph of 10 cm focal length. The spectrum of ζ Pup extended from 920 to 1360 Å with about 0·8 Å resolution. Tentative identification of 102 multiplets of both stellar and interstellar origin has been made, from which it is concluded that all lines included in existing model atmospheres have been detected with the exception of those masked by telluric N_2 or strong P-Cygni-type profiles. Additional weak absorption lines indicated a wide range of ionization and excitation entirely consistent with observations in the visible spectral region of stars of similar type; they also appeared to affect sensibly the energy distribution within the spectrum. Transitions in C III (1176 Å), N III (990, 992 Å), N IV (955 Å), N V (1239, 1243 Å), O IV (1339, 1343 Å), O VI (1032, 1038 Å), and S VI (933, 944 Å) have been observed as P Cygni profiles. Except for the S VI lines, the mean radial velocities associated with ground-state transitions and the transition from the lowest triplet state in C^{2+} ions are close to an average velocity of 1770 km s^{-1}; the mean radial velocities of the N IV and O IV ions are 530 and 150 km s^{-1}, respectively. These resultssuggest a positive velocity gradient in the observed portion of the circumstellar envelope, and they also suggest that the escaping ions are loosely bound together with essentially no difference in their average acceleration away from the star. The interstellar columnar density of atomic hydrogen was found to be $(7{\cdot}6 \pm 2{\cdot}5) \times 10^{19}$ cm^{-2}, and assuming that the line-sight through atomic hydrogen is 390 pc the mean atom density becomes $(6{\cdot}4 \pm 2{\cdot}1) \times 10^{-2}$ cm^{-3}.

The spectrum of ζ Ori extended from 922 to 1453 Å with 0·8 Å resolution. All lines used in existing models of stellar atmospheres appeared in the recorded spectrum with the exception of those masked by telluric N_2 or strong P Cygni-type profiles and an O V line at 1371·29 Å. Fifteen multiplets of subordinate lines were reliably identified indicating a range of excitation from 0 to 50 eV. Transitions of C III (1176 Å), N III (991 Å), N V (1239, 1243 Å), O VI (1032, 1038 Å), Si IV (1394, 1403 Å), S IV (1063, 1074 Å), and S VI (933, 944 Å were observed as P Cygni-type profiles presumably arising in a circumstellar envelope. The degree of ionization, transitions present, and mean radial velocities are all consistent with viewing the envelope as a hot ($\sim 10^5$ K) plasma in which collisional ionization is important. Interstellar lines of C I (1277, 1280 Å), C II (1036, 1334 Å), N I (1134–1135 Å) N I (1200–1201 Å), N II (1084–1086 Å), O I (1302, 1305 Å), Si II (1190–1193 Å), Si II (1260 Å), and Si II (1304 Å) were identified. The equivalent width of the Lα line was found to be ($10{\cdot}4 \pm 1{\cdot}6$ Å) which corresponds to a columnar density of $(2{\cdot}0 \pm 0{\cdot}7) \times 10^{20}$ cm^{-2}.

The spectrum of ζ Oph was made with a new spectrograph, again of the Wadsworth type, but with a one-meter focal length and an intended resolution of 0·1 Å from 900 to 1700 Å. On this first flight a resolution of only 0·5 Å was realized. However, this was sufficient to reveal the nine vibrational transitions from the ground state in the fourth positive system ($A\,^1\Pi - X\,^1\Sigma^+$) of $^{12}C\,^{16}O$; five similar transitions in $^{13}C\,^{16}O$ were also observed. The results appear to be consistent with viewing the molecules as being in equilibrium with a 2·7 K 'fossil' radiation field. Assuming this to be the case the column densities of $^{12}C\,^{16}O$ and $^{13}C\,^{16}O$ molecules are $1{\cdot}8 \times 10^{15}$ cm^{-2} and $2{\cdot}3 \times 10^{13}$ cm^{-2} respectively. Interstellar lines arising in C^0, C^+, O^0, Si^+, and S^+ were also observed in the ζ Oph spectrum, and abundance determinations of interstellar carbon, oxygen, sulfur and silicon were attempted. For the first three of these elements the results showed that within a factor of 10 the abundances relative to hydrogen (determined through the observed Lα line) were the same as the solar relative abundances. The relative abundance of sulfur was anomalously high. It was surmised that the sulfur lines were broadened by other unidentified features or by multiple components of the sulfur lines themselves. In addition, the $^2P^0{}_{3/2}$ (0·0079 eV) fine structure level of the C II ground state configuration was observed to be strongly populated. The abundance ratio of the

$^2P^0{}_{3/2}$ level to the $^2P^0{}_{1/2}$ level is about 1·5. One possible explanation is that the excited C^+ ions are inside the Strömgren sphere where proton densities on the order of 220 cm^{-3} can collisionally excite the ions at sufficient rates. Stellar absorption lines of C IV (1548, 1551 Å) and N V (1239, 1243 Å) were observed to be shifted to shorter wavelengths indicating stellar mass loss. The stellar material should be stopped in the H II region by coulomb forces, and it is possible that most of the C^+ ions in the $^2P^0{}_{3/2}$ level come from this source.

The IUE satellite

A. Boggess has continued to direct a design study of a geosynchronous satellite carrying a 45-cm telescope to be used for ultraviolet spectroscopy. This satellite, now designated as the International Ultraviolet Explorer (IUE), is being developed in cooperation with the UK Science Research Council and with ESRO. The telescope instrumentation consists of two echelle spectrographs, one operating from 1200 to 1900 Å and the other from 1800 to 3100 Å, having resolving powers of 10^4 or more. The spectrographs are also convertible to low dispersion instruments with resolutions of about 7 Å.

IUE spectra are to be recorded by SEC Vidicon television cameras and transmitted to the ground after each exposure. TV cameras will also view the telescope field and transmit its image to the ground for use as a finder field and to monitor the automatic guidance system. The geosynchronous orbit will permit the satellite and its telescope to be operated in real time continuously from a North American control center and for twelve hours or more each day from a European control center. The continuous control based on television displays should permit the telescope to be scheduled and operated in a fashion very similar to the use of conventional ground-based telescopes.