Ultraviolet Astronomy: Progress with the OAO

The astronomers who are using the Orbiting Astronomical Observatory (OAO) satellite to investigate ultraviolet radiation from the stars call it a truly manned unmanned spacecraft. Literally flying the satellite from the ground with the help of a team working around the clock at the Goddard Space Center of the National Aeronautics and Space Administration (NASA), the astronomers have mapped large areas of the sky in the ultraviolet and have discovered generally larger amounts of ultraviolet radiation than previously was expected. The OAO work so far has turned up some surprises and, in addition, has provided detailed information that will lead to a better understanding of stellar genesis, evolution, and decay.

The first of four planned OAO satellites was launched by NASA in 1966 but failed almost immediately because of power supply malfunction. The current satellite, OAO-II, was launched into a nearly circular earth orbit on 7 December 1968 and recently completed its 10,000th orbit, having thereby lasted twice as long as expected. The two experiments that make up OAO-II's scientific package are the sky survey of the Smithsonian Astrophysical Observatory, which has taken 8700 frames of data in mapping 10 percent of the ultraviolet sky, and the University of Wisconsin experiment, which has made more than 5000 observations in studying individual objects ranging from comets to stars to interstellar dust. The Smithsonian group, headed by Robert Davis, expects to take at least another year in cataloging some 25,000 stars before results are available; in addition to making the star maps they will eventually determine the statistical frequency of the various spectral classifications and color indices in the ultraviolet. Some results are already available from the Wisconsin experiment, which is headed by Arthur Code.

The instruments on board the OAO-II include four specially built 12-inch telescopes with imaging tubes sensitive to ultraviolet light, each in a different spectral region, for the Smithsonian Celeoscope star "photographs." The Wisconsin instruments are of two types, filter photometers of both 16- and 8-inch size and scanning spectrometers covering the range from 1050 to 3800 Å in increments of 10 to 20 Å. The pointing accuracy of the satellite is better than 1 minute of arc. OAO-III, which is to be launched 23 November if all goes well, carries an experiment from the Goddard Space Center which is expected to have a pointing accuracy of 1 arc second, and the spectrometer attached to its 38-inch telescope will have a resolution of about 2 Å, five times that of OAO-II. The OAO-IV will carry a Princeton University spectrometer with a resolution of 0.1 Å, which will be accurate enough to identify the absorption lines of a large number of molecules, although at some sacrifice in light-gathering power.

Comets and Planets

The astronomers working with OAO-II will tell you that one of the important features of the satellite is its flexibility as an observatory. For example, phenomena that appear suddenly can be examined even though they are not what the facility was originally designed for. Thus, the University of Wisconsin group was able to take advantage of the special viewing opportunity provided by the appearance of comets Tago-Sato-Kosaka (1969g) and Bennet (1969i). Observations of these targets resulted in the discovery of a large cloud of atomic hydrogen surrounding the comet, as was first predicted by L. Biermann of the Max Plank Institute in Munich. Surprisingly, the observations also showed the presence of a spectral line due to the OH radical which was much stronger than those due to CN (cyanogen) or the diatomic carbon molecule C_2, found with ground-based telescopes. Apparently OH is several hundred times as abundant in these comets as CN or C_2. Finding OH in addition to the hydrogen envelope led the Wisconsin researchers to suggest that one of the main constituents of comets is ordinary water in the form of ice, along with methane ice and trace compounds. As the comet approaches the sun all of these materials presumably melt, evaporate, and dissociate because of the intensifying solar radiation, giving the observed breakdown products.

Spectral scans of the major planets of the solar system show a high degree of consistency, an indication that the solar spectrum is the source of the observed lines. Planetary albedos (the amount of light reflected by the planet's atmosphere compared to that incident upon it) have been computed with the use of an adopted solar spectrum. Jupiter's albedo shows little variation in the near ultraviolet range, and that of Mars increases toward shorter wavelengths and appears to agree with that calculated for a CO_2–ozone atmosphere.

Interstellar Extinction

Essentially no electromagnetic radiation with wavelength shorter than 3000 Å penetrates the earth's atmosphere, so that astronomic investigations of the ultraviolet spectrum necessarily involve balloon, rocket, and satellite observations. Because the incoming ultraviolet radiation is so attenuated compared to the visible and infrared wavelengths, much more is typically known about relatively cool astronomical objects that radiate in the visible or red regions. Hence one of OAO's primary goals has been to study the young, hot, ultraviolet-radiating stars in order to obtain energy distributions of diverse spectral types for comparison with model atmosphere calculations.

Before these energy distributions could be measured, however, the reddening effect often caused when light from the stars is scattered and absorbed by clouds of dust in the interstellar regions had to be determined. The Wisconsin group compared the light received from pairs of stars of the same spectral type but of different colors; they then took the ratio of intensities to find the percentage of light removed at each wavelength. Their results confirm and extend the earlier indications from rocket measurement by Albert Boggess and T. P. Stecher of the Goddard Space Center that interstellar extinction is not as high in the ultraviolet as a linear extrapolation of ground-based observations would suggest. The OAO-II observations from more than 100 pairs of stars show that when extinction is plotted against wavelength, the resulting curves have a pronounced peak near 2200 Å followed by gradual increases in extinction toward shorter wavelengths.

Just how the light is dimmed at different wavelengths depends on the size and distribution of the dust particles. Unlike interstellar gas molecules, which absorb light only at certain wavelengths, dust absorbs at all wavelengths; blue light is absorbed more effectively than red because blue wavelengths are more comparable to the particle sizes, and thus produce a net reddening effect. The amount of extinction is, however, not constant in all directions of space. The OAO-II team observes variations in interstellar extinction from star to star which, they feel, may depend upon local effects such as the possibility that small particles are evaporated or blown away by radiation pressure in the neighborhood of very hot stars.

The chemical nature of the interstellar dust is still a mystery to astronomers. The peak at 2200 Å in the extinction curves obtained with OAO-II may indicate the presence of graphite, but higher resolution measurements are required for definitive identification. Other observations of circumstellar extinction have suggested that particles like magnesium silicate and silicon carbide may also be present. In recent years astronomers studying mass loss from stars have predicted that cooling and condensation of stars would produce all these particles. It is also known that very massive stars seem to form only in very dusty regions, and it is believed that the dust plays an important role in the formation process by cooling gas clouds so that they can collapse. Hence the composition and properties of the interstellar dust, which may be given off by old stars and contribute to the formation of new ones, are of considerable significance for the prediction of the future of the galaxy as well as for the interpretation of interstellar extinction.

Stellar Atmospheres

When the energy distributions of ultraviolet stellar radiation obtained by OAO-II are corrected for the effects of interstellar extinction, the temperature scales found for some spectral classes of stars appear to differ from those previously used. Higher effective temperatures (2000°K and more) are indicated by the Wisconsin group's results for the hotter, early-type stars, while the previous temperatures for the cooler spectral types seem to be correct.

Ultraviolet excesses have been found in the spectra of several late-type giants and supergiants, and these seem to be due to emission lines rather than to absorption lines, indicating that these stars have coronas and chromospheres. Previously only the chromospheric activity of the sun has been amenable to observation; however, the big red giants are relatively cool stars and give off little photospheric radiation in the ultraviolet, so that chromospheric radiation can be seen. The emission lines, primarily from the MgII doublet at 2800 Å, are known to represent chromospheric processes, whereas radiation from the star itself would be seen as an absorption line. This difference reflects the reversal of the temperature gradient in the chromosphere. These observations on stars very different from the sun will give a clearer view of the coronal process that results in the solar wind and will provide a check for model stellar atmospheres that must be matched to the nonequilibrium coronal and chromospheric phenomena in the future.

High velocity mass loss from hot, early-type supergiants was reported by Don Morton of Princeton University in 1967 on the basis of rocket observations. These findings have been confirmed by Code's group with the OAO-II. Absorption lines from SiIV and CIV appear shifted from their normal positions toward shorter wavelengths by as much as 9 Å. This "inverse red shift" corresponds to a velocity toward the earth of 1900 kilometers per second and may represent a mass loss from these hot blue stars of as much as 10^{-6} solar masses per year. Such a mass loss would be significant both for the evolution of the star and for the dynamics of the interstellar medium.

OAO-II has been used to observe a number of variable star systems in order to find better solutions for their orbits and hence more accurate values for their luminosities. Light curves for eclipsing binaries such as U Cephei and VV Orionis have been obtained throughout the ultraviolet, thus creating the wide wavelength baseline necessary for the study of systems composed of both a hot and a cool star, one of which is almost invisible at either end of the spectrum.

Attempts to find spectral effects from the strong latitudinal temperature variation thought to exist on rapidly rotating stars has so far met with no success. Large rotational effects were predicted in the ultraviolet range, but do not seem to be present. Silicon stars—so-called because of their relatively high trace concentrations of silicon—are known to be fainter in the ultraviolet than normal stars of the same spectral type, but detailed spectra obtained with the OAO-II suggest that the lower intensity is due to the combined absorptive effects of several heavy elements rather than to silicon alone. Code's group is still in the process of reducing more recent data which will provide checks on other features of model stellar atmospheres; they hope to test various predictions of the effects of convection, departure from local thermodynamic equilibrium, and varying chemical composition on the stellar spectrum.

Galactic and Extragalactic Radiation

Several galaxies and extragalactic nebulas observed with the OAO-II appear to be bluer than would be expected on the basis of extrapolations from ground-based energy curves. Studies of galaxies such as Andromeda show that some of the excess ultraviolet radiation comes from a region near the stellar nucleus, an indication that the radiation may result from a galactic nucleus process. The nature of this ultraviolet excess may be significant in determining the kinds of stars found in the galaxies and in understanding the energetic processes occurring in the nucleus. The ultraviolet excess will also modify calculations of extragalactic sky brightness. A determination of exactly how large the ultraviolet excess observed really is will have to await final calibration of the OAO-II telescopes from rocket shots that provide independent measurements of reference stars.

In addition to their role in calibrating satellite instruments, rockets have been primary vehicles for making ultraviolet observations of stars for 15 years and astronomers using them continue to make significant discoveries. Along with the findings of mass loss from stars and the early measurements of interstellar extinction mentioned above, both of which have been verified and expanded by the OAO-II, recent rocket observations by George Carruthers of the Naval Research Laboratory have added molecular hydrogen to the list of interstellar species that have been identified (*Science*, 9 October 1970, pp. 149–150). The resolution of the present OAO is fairly poor at the short wavelength end of its range where the molecular hydrogen absorption lines occur, so that it has not been able to follow up on this discovery. However, the later OAO's with higher resolution undoubtedly will.—ALLEN L. HAMMOND