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Early ultraviolet spectroscopy from space

The period starting around 1950 and extending into the twenty-first century will probably ultimately be remembered as the golden age of discovery in observational astronomy. This is because of the simultaneous occurrence of three technological advances: the ability to observe the entire electromagnetic spectrum, by combining observations from the ground and from above the absorbing effects of the Earth's atmosphere; the creation of efficient and high-precision detectors of electromagnetic radiation; and the development of computers for processing and manipulating large electronic data sets. The field of ultraviolet (UV) astronomical spectroscopy at wavelengths shorter than 3100 Å has benefited from all three of these technological revolutions and has required access to space for its very existence.

In this chapter I follow the development of the field of UV astronomical spectroscopy from space over the period from approximately 1945 to 1980, with the emphasis on spectroscopy of objects located beyond the Solar System. The discussions concentrate on scientific developments in the wavelength range from ~900 to ~3100 Å. The lower limit of ~900 Å represents the wavelength where bound–free opacity of neutral hydrogen in the interstellar gas becomes large, and the upper limit of 3100 Å is where observations begin to become possible from telescopes situated on the ground. The wavelength regions of 100–900 Å, 900–1200 Å, and 1200–3100 Å are usually referred to as the extreme ultraviolet (EUV), far-UV, and UV regions of the spectrum, respectively. I shall not review the beginnings of EUV spectroscopy from above the atmosphere since those beginnings were delayed by a decade compared with activities in the far-UV and UV bands; for a review of the beginnings of EUV astronomy see Bowyer (1991). This delay resulted mostly from the fear that the interstellar H I opacity in most directions would be so large that only the stars closest to the Sun would be observable. However, the highly irregular distribution of H I in the local interstellar medium and the existence of the local hot bubble of ionized hydrogen rendered these fears invalid. EUV astronomy achieved its first photometric detection of a stellar source during the Apollo–Soyuz mission (Lampton *et al*. 1976) and the first low-resolution EUV stellar spectra were obtained several years later (Holberg *et al*. 1980) as part of the Voyager 1 mission.

In preparing this historical overview of developments in the field of UV astronomy from space, I benefited substantially from reference to various papers summarizing the state of UV astronomy over the past 40 years. These include the reviews by Friedman (1959), Wilson and Boksenberg (1969), Wilson (1970), Bless and Code (1972), Code and Savage (1972), Spitzer and Jenkins (1973), Boggess and Wilson (1987), and Brosch (1999).

THE OBSCURING ATMOSPHERE

The attenuation produced by the Earth's atmosphere in the UV as a function of wavelength in angstroms is shown in Figure 1. The solid curve gives the altitude in kilometers at which radiation normal to the atmosphere is reduced in intensity by a factor of 1/*e*. The various molecules and atoms mostly responsible for the atmospheric absorption are indicated on the curve. The atmospheric absorption that rapidly sets in near 3100 Å is produced by ozone (O_3) while

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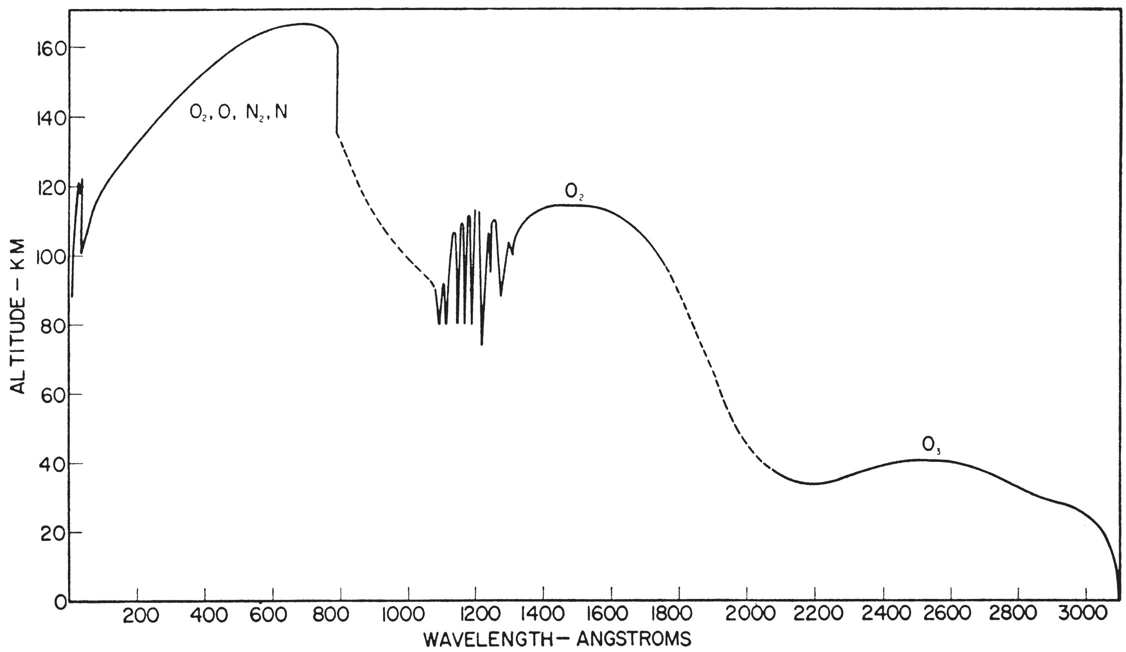

Figure 1 This figure from Friedman (1959) shows the altitude in kilometers at which the fraction of radiation at wavelengths shorter than the visible incident on the Earth's atmosphere is reduced by a factor of 1/*e*. Strong atmospheric absorption due to O_3 sets in at about 3100 Å. While in the mid-UV it is possible to carry out observations from high-flying balloons, satellite altitudes are required to observe celestial sources for the UV wavelengths below ~2000 Å. (By permission of the *Journal of Geophysical Research*.)

absorption at shorter wavelengths is mostly from O_2, O, N_2, and N. In the wavelength range ~2000–3000 Å it is possible to carry out UV observations from balloons carried to altitudes of 30–40 km (see later section on Near-UV Spectroscopy from Balloons). However, rocket or satellite altitudes are required to observe at UV wavelengths shorter than ~2000 Å. Even at rocket or satellite altitudes exceeding 300 km, the trace atomic constituents in the atmosphere can interfere with astronomical observations. In particular, the hydrogen geocorona extends many Earth radii from the surface of the Earth, and the H I scatters sunlight in the Lyman series lines producing very strong emission, particularly in the Lyman α, β, and γ lines at 1215.67, 1025.72, and 972.54 Å. Similarly, Earth airglow emission can be strong in various O I transitions. Even at the altitudes of the major modern observatories such as the Hubble Space Telescope, there is enough residual O I in the atmosphere for terrestrial O I absorption lines to be apparent in high-resolution spectra of hot stellar continuum sources.

THE SCIENTIFIC IMPORTANCE OF ACCESS TO SPACE

More than 75 years ago, Oberth (1923) pointed out that an astronomical observatory orbiting above the Earth's atmosphere would have several major advantages over an observatory on the Earth's surface. He noted that at optical wavelengths the orbiting observatory would not suffer the blurring effects of the Earth's atmosphere. Therefore the orbiting observatory could produce images limited only by the quality of the telescope optics and its pointing system. He also pointed out that the orbiting telescope would be capable of observing celestial objects over the entire electromagnetic spectrum, including spectral regions that are not accessible to the ground-based observer. No professional astronomers took these ideas seriously when they were first discussed, and over the subsequent 20 years the only other published speculations about observatories in space that I am aware of appear in the science fiction literature (Richardson 1940). However, everything changed after World War II, in part as a result of the development and capture of the V2 rocket technology and the start of the Cold War between the United States and the Soviet Union.

The first truly serious discussions of the potential scientific importance of placing satellite observatories instrumented for UV spectroscopy above the absorbing atmosphere are found in an internal report entitled "Advantages of an Extra-Terrestrial Observatory," written for the Rand Corporation in 1946 by Lyman Spitzer reprinted in Spitzer (1997). Spitzer's report discusses the science that could be pursued with several types of orbiting observatories of different sizes. In addition to observatories designed to observe the Sun in the UV, he discussed the scientific potential of a modest 0.25 m (10-inch) reflecting telescope designed to obtain UV spectra of stellar sources, and the potential value of a large reflecting telescope operating at optical wavelengths.

The scientific programs Spitzer proposed for this instrument included:

- studies of the composition of planetary atmospheres
- measures of the structure of stellar atmospheres, including the possibility of detecting expanding atmospheres in the strong absorption lines of C, N, and O
- measures of the color temperatures of hot stars
- measures of stellar bolometric magnitudes
- the analysis of eclipsing binary UV light curves to obtain information about stellar masses and atmospheric properties
- using the improved understanding of stellar atmospheric conditions from the UV studies to improve on stellar distance determinations
- measures of the composition of the interstellar gas
- measures of the properties of interstellar absorbing grains
- measures of the UV spectra of supernovae in order to better understand the explosion processes.

For each of these topics Spitzer discussed how observatories above the atmosphere could be used to make major advances in the given science area. For example, in the case of measuring the composition of the interstellar gas, Spitzer pointed out that in interstellar space most atoms and molecules were expected to be found in their ground (lowest-energy) state. Therefore measures of the composition of the gas through absorption line spectroscopy would require an observatory operating at UV wavelengths since most absorption lines out of the ground state of abundant atoms fall in the UV. Slightly more than 25 years after creating this vision for the future of UV astronomy in space, Spitzer pioneered UV studies of the interstellar medium by using the high-resolution UV spectrograph aboard the Copernicus satellite (see the section on the Orbiting Astronomical Observatories).

Shortly after the launch of Sputnik in 1957 and the organization of NASA in 1958, several papers appeared discussing the science that could be pursued with UV spectrometers operating above the Earth's atmosphere, including those of Spitzer and Zabriskie (1959) and Code (1960). I find the Spitzer and Zabriskie paper, entitled "Interstellar research with a spectroscopic satellite," particularly interesting because my professional field of interest is the interstellar medium. I remember referring to that paper in 1965 when taking Professor Spitzer's course on "Physical Processes in the Interstellar Medium." During the course I recall a particularly interesting class assignment. Professor Spitzer asked his students, "What observations would you obtain with a 1 meter satellite observatory equipped with a high-resolution spectrometer operating from 912 to 2000 Å in order to obtain information about the physical properties of the gas between the stars?" In answering the question I was intrigued by the possibility of using a satellite observatory to study aspects of the interstellar gas (the hot phase) that were difficult or impossible to study from the ground. I didn't realize at the time that this assignment was one I would continue to work on for most of my professional career.

TECHNOLOGICAL CHALLENGES

The technological challenges faced by the pioneers of UV spectroscopic space astronomy were considerable. They included gaining reliable access to space, developing small light weight UV spectroscopic optical systems, developing rocket and satellite pointing and control systems, and developing efficient UV sensitive detectors. The most difficult challenge was to design and build complex robotic systems that would actually operate in the space environment.

The progression through these various technological challenges did not always proceed smoothly. As a beginning graduate student in 1964, I witnessed the activities around Princeton University involving the pioneering projects in UV spectroscopy through the efforts of Donald Morton and Lyman Spitzer and in optical diffraction limited imagery through the Stratoscope II balloon-borne telescope program involving Robert Danielson and Martin Schwarzschild. I vividly remember discussions in the halls about rockets blowing up on the launch pad, pointing and control systems that failed to operate, rocket parachute systems that deployed too early, and balloon flights where the 3600 kg Stratoscope II telescope system failed to unlatch from the vertical pointing position, or where the sealed door on the pre-cooled 0.9 m diffraction-limited primary mirror failed to open at altitude. Reflecting on all these problems and wondering how long it might take to complete an experimental thesis in space astronomy, I made an arrangement with Robert Danielson and Martin Schwarzschild to pursue a theoretical PhD thesis and to briefly join the Stratoscope II team following my graduation to continue to explore my experimental interests. The lesson I learned during this period was that the most difficult technical challenge faced by the early pioneers in space astronomy was to achieve a high level of reliability for remotely controlled robotic systems operating in the space environment. Even today, it appears that this is a difficult goal to meet on a regular basis.

SOUNDING ROCKET SPECTROMETERS

UV space astronomy began as an experimental field at about the same time as Spitzer was considering its future.

Using captured German V2 rockets which could carry a 1000 kg of equipment to 150 km altitudes, scientists working at the Naval Research Laboratory (NRL) led by Richard Tousey obtained the first UV spectrum of the Sun to wavelengths as short as 2200 Å (Baum *et al.* 1946). The first UV stellar photometry followed about ten years later when NRL scientists observed 59 hot stars in a 130 Å wide UV band centered on 1115 Å (Bryam *et al.* 1957). These early UV stellar observations involved scans of the sky with simple photometer systems from unstabilized sounding rockets.

The flight of a scanning objective grating spectrometer on an unstabilized Aerobee rocket produced the first low-resolution UV stellar spectrophotometry over the 1600–4100 Å region at 50 Å resolution (Stecher and Milligan 1962). In this observation the dispersion direction of the spectrograph was normal to the rocket roll axis. The roll of the rocket produced the spectral scan at the slit with a photomultiplier recording the spectrum. However, to capture enough photons during the short intervals for which the stars were in the field of view, the slit needed to be wide and the resulting resolution of 50 Å was insufficient to resolve discrete stellar absorption or emission lines.

The first moderate-resolution spectroscopic observations of stars required the development of three-axis stabilization systems for pointing rocket-borne instruments at stars for long enough periods of time to record the spectra. The pointing control system developed by the Space General Corporation was a three-axis stabilized gas reaction system that could be used to orient the entire sounding rocket during its free fall. This system could point the payload within 3° of a desired direction and was stabilized to a limit cycle jitter of ± 15 arc minutes. In their pioneering experiment, Morton and Spitzer (1966) employed an additional fine stabilization system as part of their instrument package which improved the pointing in the spectrograph dispersion direction to approximately ± 16 arc seconds. Their instrument (Figure 2) consisted of two 1200 lines/mm objective plane gratings followed by *f*/2 Schmidt cameras with 100-mm focal lengths and 10° fields. One Schmidt corrector was made of calcium fluoride and transmitted to 1250 Å; the other corrector was quartz and transmitted to 1700 Å. The resulting UV spectra had a dispersion of about 65 Å/mm and were recorded on UV sensitive Kodak Pathe SC5 film. This small pair of UV spectrometers produced spectra with a resolution of approximately 1 Å when the fine stabilization platform achieved its design pointing stability in the dispersion direction.

The pioneering attempts to obtain UV spectroscopic observations of stars did not achieve instant success. During these learning stages there were often problems associated with making the attitude-control pointing systems work properly. For example, quoting from the abstract

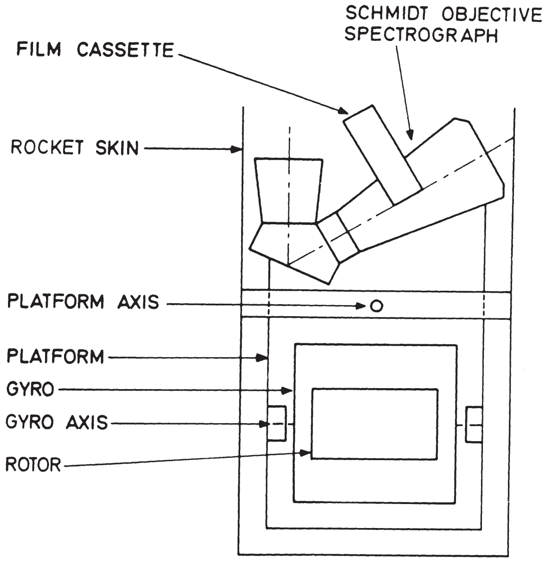

Figure 2 A schematic diagram of the simple UV spectrometer and fine stabilization system flown on an Aerobee rocket by Morton and Spitzer (1966). The fine stabilization in the spectrometer's dispersion direction allowed the instrument to obtain UV spectra of π and δ Sco from 1260 to 1720 Å at a resolution of 1 Å. (By permission of Donald Morton and the *Astrophysical Journal*.)

of the paper by Morton and Spitzer (1966) reporting the observations of first line spectra of stars in the UV,

> On the first two flights the attitude control system failed to stabilize the rocket. On the third flight both coarse and fine systems worked properly, but the parachute failed on re-entry so that the impact damaged the payload beyond repair and admitted light into the film cassettes. Most of the films were totally fogged, but underdeveloping one from the calcium fluoride camera showed wide spectra of the early B-type stars δ and π Sco with a resolution of 1 Å.

I can recall the gloomy mood after this third flight among the returning Princeton scientists and engineers when they discussed their totally blackened images. However, that mood quickly changed to one of joy when the last piece of film was underdeveloped, and revealed clear spectra of π and δ Sco extending from ~1260 to 1720 Å.

One year after the success of obtaining the first moderate-resolution UV spectra of stars in Scorpius, Morton (1967) obtained high-quality spectra of six stars in Orion at 3 Å resolution from 1150 to 1630 Å. Those data provided the first evidence for high-speed mass loss from hot stars in the form of P Cygni profiles of the Si IV and C IV stellar absorption lines (Figure 3). This result must have pleased Lyman Spitzer since in his 1946 Rand Corporation study he remarks that, "In addition the nature of unusual stellar http://www.springer.com/978-0-7923-7196-0

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