



The Space Congress® Proceedings

1981 (18th) The Year of the Shuttle

Apr 1st, 8:00 AM

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OPTICAL ASTRONOMY FROM ORBITING OBSERVATORIES

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ABSTRACT

Atmospheric extinction, seeing, and "light pollution" are the most significant factors affecting the quality of observations obtained from ground-based optical telescopes, degrading resolution and limiting reach. In addition, the earth's atmosphere is opaque to radiation shorter than 0.3 microns preventing the ultraviolet from being observed in detail from the ground. The solution to these problems has been to move astronomical telescopes into earth orbit. Initially these orbiting observatories carried instruments sensitive to ultraviolet and higher energy radiation since it was otherwise unobservable. The success of the first series of these orbiting observatories, the Orbiting Astronomical Observatories (OAO), established these satellites as one of a new generation of tools for exploring the universe. Another orbiting observatory, the International Ultraviolet Explorer (IUE), is unique among the current orbiting observatories in that it is in a geosynchronous orbit and provides a guest observer facility serving the international community. IUE has had a significant impact on observational astronomy. Nearly 10 percent of all observational papers published in the Astrophysical Journal in 1980 reported or used observations made by IUE. The figure for all astronomical satellites is about 3 times higher and continues to rise. With the orbiting of the Space Telescope in the mid 1980s by the Space Shuttle, observational astronomy will enter a new era. For the first time, astronomers will have access to a large (2.4 meter) high-resolution telescope unhindered by the earth's atmosphere. With the potential such an instrument offers, there is little doubt that the near future will see a large fraction of observational astronomy performed from orbiting observatories.

INTRODUCTION

By far the most significant factor affecting the quality of astronomical observations, at optical wavelengths (here defined to include

ultraviolet, visible, and infrared wavelengths) conducted by modern ground-based observatories is that of atmospheric extinction and seeing. Irregularities in the earth's atmosphere tend to degrade star images to much below the performance potential of good instruments. Even under the best observing conditions with the best ground-based instruments, a resolution of 0.5 arc seconds is the best that can be obtained and then for only a short period of time. Modern optical telescopes are theoretically capable of doing nearly an order of magnitude better. For optical surfaces whose irregularities are a small fraction of the wavelength of light, the theoretical resolution in seconds of arc is given by $25\lambda/D$, where λ is the wavelength of the incident light in microns and D is the diameter of the objective in centimeters. For a telescope such as the Kitt Peak 4-meter, a theoretical resolution of about 0.03 arc seconds is possible in green light. In addition to limiting the resolution of ground-based telescopes, the atmosphere absorbs most of the radiation shorter than about 0.3 microns preventing studies of astronomical objects at those wavelengths. This is of particular importance to the study of young hot stars whose energy output peaks at ultraviolet wavelengths. Also, of increasing concern to astronomers is the problem of "light pollution," airglow and scattered light from cities, which increases the brightness of the background sky making it more difficult to observe faint objects.

The solution to these problems has been obvious for a long time but it was not until the creation of the National Aeronautics and Space Administration (NASA) in late 1958 that the opportunity for conducting astronomical observations from space arose. It was shortly after its creation that NASA invited interested astronomers in to discuss the possibility of orbiting an astronomical satellite. It was from these discussions

that the Orbiting Astronomical Observatories (OAO) were conceived. Two of the four satellites in the OAO series, OAO-2 and OAO-3 (Copernicus), became fully operational. The first of these, OAO-2, was placed in a low circular orbit in December 1968 and carried two experiments designed to make ultraviolet observations of stars, nebulae and star fields. The second, OAO-3, which was named Copernicus in honor of the great 16th century astronomer, was launched in April of 1972 also in a low circular orbit. It carried an X-ray experiment and a 32-inch telescope for ultraviolet astronomy. The latter was, at the time, the largest astronomical telescope to be placed in orbit.

Both of the OAO spacecraft were low-orbiting observatories whose access was basically limited to the principal investigators who had proposed the experiments carried on board. In contrast, the International Ultraviolet Explorer (IUE), as its name indicates, is an international observatory. It is open to anyone in the world whose program of observation is accepted by the Observatory. In a synchronous orbit above the Atlantic Ocean, IUE is in constant contact with one of its two ground stations, either at the Goddard Space Flight Center (GSFC) in Greenbelt, Maryland, or the European station at Villafraanca del Castillo, Spain (VILSPA). IUE is operated in much the same way as a ground-based observatory like the Kitt Peak National Observatory. Guest Observers whose proposals have been accepted arrive at one of the two ground stations at their designated times and conduct observations in real-time. The scientific instrument carried on board IUE is a 45-cm telescope with two spectrographs for obtaining spectra of a variety of astronomical objects at ultraviolet wavelengths. Now in its fourth year of operation, IUE is expected to continue providing astronomers with ultraviolet spectra for the remainder of its nominal 3-to 5-years lifetime and in all probability for years afterward.

In the mid 1980s, IUE will be joined by the Space Telescope (ST), the largest astronomical instrument to be placed in orbit yet. Carried into orbit by the Space Shuttle, the ST is a high-resolution 2.4-meter telescope which is designed to generate a long-term program in space astronomy providing astronomers with a capability not achievable by any current or foreseeable ground-based telescope. The ST shares some of the characteristics of the OAOs and IUE. It will be a low-orbiting spacecraft, so operation of the scientific instruments will be by means of a pre-planned program, as it was for OAO. After ST's first few months of operation, it will be available as a Guest Observer facility serving the international community, as is IUE.

In this paper we present a description of the similarities and differences between these

orbiting observatories, their scientific instruments, and modes of operation. We will report some of the significant discoveries by each, or in the case of ST, the expected capabilities.

ORBITING ASTRONOMICAL OBSERVATORIES (OAO)

The first of the successful OAO spacecraft, OAO-2, was launched on December 7, 1968, and placed into a circular orbit at an altitude of 490 miles with a period of about 100 minutes. On board were two telescope systems for measuring star brightness in the ultraviolet and for obtaining low-resolution spectra. The configuration of the spacecraft was to have the two experiments located at opposite ends of the satellite. At one end was the Smithsonian Astronomical Observatory's (SAO) Telescope experiment, and at the other the University of Wisconsin's Wisconsin Experiment Package (WEP).

The Telescope experiment was designed to produce television pictures of 2-degree-square areas of the sky in ultraviolet light, the principal objective being to measure the ultraviolet magnitudes of very many stars in a statistically significant fraction of the sky. The instrument itself consisted of four 12.5-inch Schwarzschild telescopes using specially developed Westinghouse Uvicon ultraviolet sensitive television tubes, and an electronics package to control the operation of the Uvicons and to encode the data for transmission. Two types of Uvicons sensitive to different wavelength ranges were used. One type was sensitive to the range 1050-3200 Å and the other from 1050-2000 Å. The field of each Uvicon was optically split into two areas of different sensitivity by mounting two different semicircular filters in the focal plane of the photocathode. The photoelectrons emitted by the photocathode were imaged on a target where the image was integrated and stored as an electrical-charge pattern for readout at the desired time.

The sensitivity of the Uvicons during orbital operations decreased with time, but the pre-launch goal of one year of operation was still exceeded by 4 months. Telescope was turned off in April 1970.

The second experiment carried by OAO-2, the WEP, consisted of five telescopes (a 16-inch and four 8-inch) employing photoelectric filter photometers over the spectral region from about 1200Å to 4000Å, and two objective-grating scanning spectrometers which view areas 2-1/2 degrees long (in the direction of dispersion) and 8 minutes of arc wide. The spectrometers provided resolution of about 10Å in the wavelength range 1100Å to 2000Å and about 20Å in the range 2000Å to 4000Å. The WEP was operated until February 1973.

The scheduling of observations and control of a low earth orbiting observatory like OAO were not trivial functions. Observations had to be scheduled so that they did not interfere with ground contacts. Also the various constraint regions had to be avoided. Observing was forbidden within 45° of the sun and within 30° of the anti-sun (to prevent heating of the instrument at the opposite end of the spacecraft). Due to the high radiation levels encountered in the South Atlantic Anomaly, observing was not scheduled when the spacecraft was in that area. It was also desirable to avoid observing when the spacecraft was in direct sunlight due to the high level of background illumination. These and other constraints made efficient scheduling of observations a difficult process which had to be well planned in advance.

Pointing of the spacecraft to one minute of arc accuracy was possible with a tracking accuracy of about one arc second. The primary orientation was provided by six gimbaled star trackers with three or more locked onto guide stars. Flywheels inside the spacecraft then kept the star trackers on their guide stars.

The second of the OAO series to become fully operational, OAO-3 better known as Copernicus, was launched on August 21, 1972 into a nearly circular low orbit with a period of approximately 100 minutes. Very similar to OAO-2 in its operation, Copernicus did include a few improvements such as improved sun baffles, a tracking accuracy to 0.1 arc seconds and a gyro inertial reference unit as the primary attitude sensor to be augmented by four star trackers. (The pointing stability of the spacecraft during actual operations routinely reached 0.03 arc-second, and for short periods of time 0.003 arc-second stability was achieved). Also carried on Copernicus was an on-board-computer (OBC) which allowed automatic operation of the spacecraft during intervals between daily ground contacts.

The main scientific instrument carried by Copernicus, the Princeton Experiment Package (PEP), consisted of two experiments. One, an X-ray detector, will not be discussed here. The second was a 32-inch telescope with Cassegrain optics feeding a scanning spectrometer. Scanning was done by means of two carriages moving a pair of exit slits and ultraviolet sensitive phototubes. One carriage scanned the first-order spectrum from 1623\AA to 3185\AA and the second order from 711\AA to 1492\AA . The scanning was done simultaneously with one phototube observing the first order at 0.05 \AA intervals and the second phototube working at 0.025 \AA intervals. The second carriage worked in a similar way scanning 1550\AA to 3300\AA in 0.4 \AA steps and 775\AA to 1650\AA in 0.2 \AA steps.

Copernicus far outlived its nominal lifetime of one year and was only just shutdown in

February 1981. Because of the satellite's excellent stability and the high resolution and wide observing range of the primary experiment, many observations were made which cannot be made by any other astronomical satellite now operating or in the planning stage.

The OAO series of orbiting observatories has made many contributions to science. Some of the more significant discoveries and observations are listed here:

OAO-2

- 8500 television pictures of stellar fields in ultraviolet light, covering 10% of the sky,
- First systematic observations of the interstellar medium. Interstellar gas was studied by neutral hydrogen Lyman alpha measurements. Properties of interstellar dust (chemical composition and size distribution) were investigated by studying the shape and structure of the extinction curve of hot stars, including the prominent 2200\AA dust absorption feature. Small carbon grains were found to be the main ingredient of the interstellar dust,
- First observations of a comet in the vacuum ultraviolet (Tago-Sato-Kosaka 1969g) revealing among other things the extensive Lyman alpha hydrogen halo first predicted by Biermann and Trefftz Z.Astrophys. 59, 1 (1964)),
- First observations of a nova in the vacuum ultraviolet (Nova Serpentis 1970),
- Valuable light curves of variable stars such as pulsating Cepheid variables and eclipsing binary stars, and first ultraviolet observations of cataclysmic variables and faint blue stars,
- First ultraviolet flux distributions of galaxies of different Hubble types.

OAO-3

- Observations giving valuable information on the composition and physical properties of both H I clouds and circumstellar H II regions. For H I regions with strong H_2 lines the observations indicate mean temperatures of about 80 $^\circ\text{K}$, particle densities between 10 and 1000 cm^{-3} and a depletion of heavy elements,
- Observations of wide O VI lines indicating the presence of a high-temperature (about a million degrees) coronal gas of low

density, possibly occupying much of interstellar space,

- Observations of chromospheres and coranae of cool stars,
- Mass loss in hot stars.

INTERNATIONAL ULTRAVIOLET EXPLORER (IUE)

As a result of recommendations made by the NASA Astronomy Mission Board on an integrated space astronomy plan for the 1970's and from a study by the Astrophysics Research Unit of the United Kingdom's Science Research Council concerning a 45-cm telescope with an echelle spectrograph, work began in mid-1970 on the development of an Explorer-class satellite and an associated system able to operate as a guest observer facility. The end result of this work was the International Ultraviolet Explorer (IUE) launched in 1978 and placed in a geosynchronous orbit. As its name indicates, IUE is an international facility, the satellite and optical instrumentation having been provided by the Goddard Space Flight Center, (GSFC) the television cameras by the United Kingdom Science Research Council (SRC) and the solar panels by the European Space Agency (ESA). The observing time on the satellite is split between the two sides of the Atlantic with two-thirds directed from one control center at GSFC and the remaining third from the European control center near Madrid.

By choosing a synchronous orbit for IUE many of the problems associated with lower orbiting satellites are not encountered, and the operation of the satellite from an observing standpoint becomes very similar to that of a ground-based observatory. The scientific objectives of the IUE project are given below:

- To obtain high-resolution spectra of stars of all spectral types in order to determine more precisely their physical characteristics,
- To study gas streams in and around some binary systems,
- To observe at low resolution faint stars, galaxies, and quasars, and to interpret these spectra by reference to high-resolution spectra,
- To observe the spectra of planets and comets as those objects become accessible,
- To make repeated observations of objects known or newly found to show variable spectra,
- To define more precisely the modifications of starlight caused by interstellar dust and gas.

The IUE scientific instrument is a 45-cm telescope with an echelle spectrograph and four SEC Vidicon television tubes (two of them in back-up cameras). The telescope is carefully baffled so that scattered light entering the tube must suffer at least two reflections from diffuse black surfaces before it can strike a telescope mirror. The instrument is capable of obtaining both high resolution (0.1Å) and low resolution (6Å) spectra in two wavelength ranges which vary slightly depending on the dispersion but cover the interval from about 1130Å to 3250Å.

The stabilization and control of the spacecraft is carried out by a set of reaction wheels which control the slews and pointing. A one-arc-second pointing accuracy is maintained by an offset star tracker. An OBC is used for all stabilization and control calculations.

Observations with IUE are performed in near real-time with the guest observer having the opportunity to take a quick look at the data received from the spacecraft. This gives the observer the ability to immediately assess the quality of the spectra and to make a decision as to whether the observation should be repeated with a different exposure time, etc. If the image is approved it is then processed with the observatory's image processing software, and the output products are quality checked and given to the guest observer with, in general, same-day or one-day turnaround time. In most cases an observer can complete his observing session on IUE and leave with all his data in both processed and unprocessed form.

IUE has just completed its third full year of operation (of a 3- to 5-year nominal lifetime) and is expected to continue for many more years. During its first three years of operation more than 19,000 images have been acquired. A few of the highlights of the first three years of observations made by IUE are given here.

- Observations of hot components in a variety of binary systems, including companions to stars not generally suspected of being binaries were made. In particular several Cepheids have been found to have relatively hot companions.
- Observations were made of symbiotic systems. These systems are stars which appear to be red giants but contain indications in their spectra that hot continua are exciting emission lines in circumstellar material.

- Observations of the supernova in M 100 which was discovered in April 1979 revealed many interesting features. Most interesting of all were the emission lines which appeared to originate in a rapidly expanding, thin, ionized circumstellar shell located well outside the exploding envelope. Observations of these lines has given some insight into the situation preceding the supernova explosion.

- Observations confirming the existence of the galactic corona were made.

- Observations were made of the two components of the quasar 0957 + 561 suggesting that both components are indeed images of the same quasar produced by a massive elliptical galaxy in the foreground acting as a gravitational lens.

SPACE TELESCOPE

While IUE continues to make observations of astronomical objects, personnel at the Marshall Space Flight Center, the Goddard Space Flight Center, and astronomers around the world await the orbiting of the Space Telescope (ST) by the Space Shuttle, currently scheduled for January 1985. The scope of the ST project is beyond that of any other astronomical satellite or ground-based observatory. It is designed as a long-term program in space astronomy providing astronomers with a capability far surpassing that of any other orbiting astronomical observatory or ground based observatory.

The ST consists of a Support Systems Module, an Optical Telescope Assembly, five focal plane Scientific Instruments, and the Scientific Instruments Control and Data Handling Subsystem. The Fine Guidance Sensors in the Optical Telescope Assembly will be used for both ST pointing and for astrometry. The ST will be placed in a circular orbit at an altitude of approximately 550 km and at an inclination of about 28° to the equator, giving a period of approximately 95 minutes. The telescope itself is an f/24 Ritchie-Chretien system with a 2.4-meter aperture, and will be the largest telescope ever orbited. It will have a point source spatial resolution of about 0.1 arc seconds with 70 percent of the total energy enclosed by a circle 0.2 arc seconds in diameter. The wavelength operating range will be from about 1150Å out to about one millimeter; however, the first group of five instruments will not exploit the entire range out to the millimeter end. Pointing and stability of the ST will be accurate to 0.007 arc seconds, slightly less in the case of objects moving with respect to the stellar background. With the combination of high resolution, low

background, increased sensitivity and large aperture the ST should reach objects 100 times fainter than those which can be seen by ground based telescopes, and with the absence of distortions caused by the atmosphere, time-resolved observations in the range of 1 msec to 1 sec will be possible.

The objectives of the ST program as stated in the Announcement of Opportunity for Space Telescope are to determine:

- the constitution, physical characteristics, and dynamics of celestial entities,
- the nature of processes which occur in the extreme physical conditions existing in and between astronomical objects
- the history and evolution of the universe; and,
- whether the laws of nature are universal in the space-time continuum.

To begin this task ST will carry five scientific instruments (it can carry as many as five at one time) when it is first placed in orbit. They will consist of the Wide-Field Planetary Camera (WF/PC), The Faint Object Camera (FOC), the Faint Object Spectrograph (FOS), the High Resolution Spectrograph (HRS) and the High Speed Photometer (HSP).

The WF/PC should be sensitive from about 1150Å to 1.2 microns and can perform imaging and filter photometry at two focal ratios with fields of view of 2.67 x 2.67 and 1.1 x 1.1 arc minutes.

The FOC will be a photon-counting system sensitive from 1200Å to 6500Å with fields of view of 11.0 x 11.0 and 22.0 x 22.0 arc seconds. Also included is a slit spectrograph mode for extended sources and a coronagraph for working near bright stars.

The FOS will provide low resolution spectra from about 1500Å to about 7000Å using a Digicon detector.

The HRS will provide moderate and high resolution spectra from 1050Å to about 3200Å also using a Digicon detector.

The HSP will provide high-accuracy photometry and high time resolution (16 μ sec) data over the wavelength range 1150Å to 8000Å using four image disectors, a photomultiplier tube and about 48 filters.

Astrometry can also be performed with ST by using the Fine Guidance System (FGS) which can determine relative positions of stars to an

accuracy of 0.002 arc seconds.

Of the many things which make ST unique among astronomical satellites, one of the most important is the capability of in-orbit maintenance of the spacecraft and the scientific instruments, and the ability to change scientific instruments in orbit. These maintenance visits are currently planned at about 2-1/2 year intervals. At approximately five-year intervals the Space Shuttle will retrieve the ST from orbit and return it to the ground for refurbishment.

Astronomers will perform observations with ST from the Space Telescope Science Institute (ST ScI) to be located at the John's Hopkins University in Baltimore, Maryland. Since ST will be a low orbiting spacecraft, observations will be conducted by means of a pre-planned program. Data will be relayed to ground stations by way of the Tracking and Data Relay Satellite System (TDRSS) and then to the ST ScI where the Institute personnel will process the data. The astronomer will also have an opportunity to "custom" process his own data.

With the difficulties involved in funding research projects one often finds it necessary to defend the worth of one experiment or another. In the case of astronomical research projects, trying to assign a value to the knowledge gained is not an easy task. One approach is to look at the relative values of certain projects. This is the approach taken by Mark Kuhner of Columbus Laboratories who has taken as a measure of an astronomical satellite's relative worth the number of published observational papers using data from that particular satellite. Kuhner showed that in 1980 nearly 30 percent of the observational papers published in the Astrophysical Journal dealt with satellite data, and in particular nearly one out of three of those papers used results from IUE. In most cases the data which have been returned by orbiting astronomical observatories are impossible to collect from ground-based observatories, and in the case of ST, data of a quality and resolution not obtainable from the ground is expected.

Since the launching of OAO-2 much has been learned concerning the techniques and procedures for operating observatories in space. This experience has culminated in the construction of the first large observatory to be placed in earth orbit, ST. Many difficulties in the operation of these observatories still remain, however. Methods and procedures for efficiently and accurately handling the large data volumes, data archiving, and data distribution are still being refined.

The new two decades will see observational astronomy dominated by the ST, and in all

probability will see orbiting astronomical observatories taking a larger and larger share of the observational workload.

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