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ASTROPHYSICAL CONTRIBUTIONS OF THE INTERNATIONAL ULTRAVIOLET EXPLORER[1]

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1. INTRODUCTION

The *International Ultraviolet Explorer* (*IUE*) was launched from the Kennedy Space Center on January 26, 1978 (Boggess et al. 1978a,b). The launch was the culmination of nearly ten years of joint study and development by the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), and the UK's Science and Engineering Research Council (SERC). The mission was conceived from the beginning as an ultraviolet spectroscopic observatory that could be used by astronomers as they were accustomed to observing from the ground, without special training in the mysteries of orbital operations. This dictated that the satellite be placed in a high orbit, and in fact an elliptical geosynchronous orbit was chosen to allow the observing to proceed at the diurnal rate and to simplify the logistics of ground stations. The disadvantage that only a small telescope could be lifted to geosynchronous orbit was offset by the multiplex advantages offered by the two-dimensional SEC (secondary electron conduction) vidicon cameras that were selected as detectors for the spectrographs. The success of the concept has been demonstrated amply by the continuing intense demand for observing time from astronomers all over the world.

The spacecraft is controlled from the NASA/Goddard Space Flight Center (GSFC) in Greenbelt, Maryland. The scientific instruments on board are operated 16 hours daily from the science operations center there and 8 hours daily from the ground station in Villafranca, near Madrid, Spain.

IUE was planned from the beginning to be a long-lived space observatory, but in the early 1970s, *IUE*'s three-year design lifetime requirement seemed like a very long life indeed to the responsible scientists and engineers. The fact that the observatory is still maintaining a full and productive observing schedule with undiminished sensitivity after more than 10 years in orbit is a tribute to the skill and commitment of those who built and have operated the satellite and ground system. The spacecraft, telescope, instrumentation, and US ground system were built by GSFC. The SEC vidicon cameras were produced by the UK's Appleton/Rutherford Laboratories, and ESA's ESTEC provided solar arrays and the European ground system.

The satellite observatory consists of a 45-cm Cassegrain telescope equipped with two spectrographs, for the 1900–3200 Å and 1150–1950 Å spectral ranges. There are two SEC vidicon detectors for each spectrograph, and primary and redundant cameras, designated LWP, LWR for the longer wavelength range and SWP, SWR for the shorter wavelength range. The observational characteristics of *IUE* are summarized in Table 1.

The scientific operations of *IUE* are normally performed in real time, with the observer at the console assisted by a Resident Astronomer and a Telescope Operator. The data are telemetered to the ground after an exposure is completed, and the reduced data are routinely available within 24 hr. At the GSFC *IUE* science operations center, a regional data analysis facility is available to facilitate prompt evaluation of the observations.

During the first 10 years of *IUE* operations, 832 different individuals used the GSFC observing facilities, while approximately 770 astronomers used the Villafranca ground station. Although observers have come from all over the world, these totals in fact represent significant fractions of the astronomers active in research in North America and Europe.

As a measure of the scientific productivity of *IUE*, we note that as of late 1987, a few weeks before the tenth anniversary of launch, 1571 papers in refereed journals were identified as based on *IUE* results. Of course, the

Table 1 Characteristics of *IUE* instrumentation

Telescope	
Clear aperture	0.45 m
Figure	Ritchey-Chretien
Focal ratio	15
Image quality	3 arcsec
Long-wavelength spectrograph	
Spectral range	1900–3200 Å
Echelle resolving power	13,000
Low-dispersion resolution	8 Å
Short-wavelength spectrograph	
Spectral range	1150–1950 Å
Echelle resolving power	12,000
Low-dispersion resolution	6 Å

most important measure of an observatory is the quality of the work; here we describe some highlights of the *IUE* research. The scope of that work is so great that we have had to omit many very significant individual findings and even several major subject areas. For more detailed information and for reviews of *IUE* results over the full range of astrophysical disciplines, the reader is referred to the compendium of review articles edited by Kondo et al. (1987) and to the proceedings of nine *IUE* symposia, especially the most recent one, *A Decade of UV Astronomy With the IUE Satellite* (*ESA SP-281*, two volumes), which contains the proceedings of a symposium held in April 1988. The dates, locations, and sponsors of the *IUE* symposia were as follows:

1979	London	SERC, ESA, and NASA
1980	Greenbelt	NASA
	Tübingen	ESA and SERC
1982	Greenbelt	NASA
	Madrid	ESA and SERC
1984	Greenbelt	NASA
	Rome	ESA and SERC
1986	London	SERC, ESA, and NASA
1988	Greenbelt	NASA, ESA, and SERC

2. STELLAR CHROMOSPHERES AND TRANSITION REGIONS

Prior to the advent of space observations in the UV, the study of chromospheres in stars other than the Sun was limited mostly to the study of the Ca II H and K resonance doublet emission lines (Wilson & Bappu 1957). In the early 1970s, a series of balloon-borne UV observations provided the spectra of the Mg II resonance doublet emission lines at 2795 and 2802 Å (e.g. Kondo et al. 1972, 1976). Observations of the Mg II doublet from *Copernicus* (e.g. Weiler & Oegerle 1979) expanded the data base. It is *IUE*, however, that has made practical an in-depth, comprehensive investigation of stellar chromospheres by extending the spectral coverage to the entire mid- and far-UV region and by enabling observations of much fainter objects. For recent reviews of *IUE* results on this subject, see Jordan & Linsky (1987) and Dupree & Reimers (1987). In addition, there are valuable reviews on chromospheres and related subjects in the proceedings of the above-mentioned *IUE* symposia. Following these review papers, some principal findings from the *IUE* on stellar chromospheres can be summarized as follows:

1. Observations of chromospheric emission have been expanded to include stars as early as spectral type A and as late as M dwarfs (e.g. Brown & Jordan 1981, Ayres et al. 1981); such emission also has been detected in evolved stars in this spectral range (e.g. Linsky & Haisch 1979, Dupree et al. 1979, Brown et al. 1979, Carpenter & Wing 1979). This has permitted the correlation of various stellar parameters that pertain to subphotospheric convection zones with chromospheric emission. Empirical relationships between the stellar age and rotation and the chromosphere and transition regions have also been established. Rotation enhances the level of emission, and as the star evolves, stellar winds tend to brake the rotation, so that the emission fluxes generally decrease (e.g. Hartmann et al. 1984). As a star evolves, the decay of magnetic activity in the outer atmosphere can occur more rapidly at lower levels than at higher ones (Simon et al. 1985).

2. Detailed studies of emission-line fluxes and line widths suggest that for stars later than mid-F, chromospheres are heated primarily by magnetic fields or stellar dynamo processes (e.g. Parker 1970, Ayres & Linsky 1980), but that for stars earlier than mid-F and for weak chromospheres, the heating may be dominated by acoustic waves.

3. The chromospheric properties of single stars can be considered in terms of solar-type, non-solar-type, and hybrid stars. A solar-type star has a hot transition region (temperatures in the range of a few hundred thousand degrees) and a coronal temperature in the range of millions of degrees. A non-solar-type star lacks a hot transition region but has a massive, cool stellar wind. A hybrid star has both a hot transition region and a massive, cool wind. The demarcation line between the solar-type and non-solar-type stars in the Hertzsprung-Russell (HR) diagram is somewhere

near spectral class Kl III (Linsky & Haisch 1979, Mullan & Stencel 1982).

4. Chromospheres in close binary stars are often markedly different from those in single stars. A late-type star in a close binary system rotates more rapidly than a single star owing to its tidally locked rotation. Loss of angular momentum through winds leads to slower rotation in a single star, but in a binary the loss of the angular momentum is compensated for by the large orbital angular momentum. Faster rotations in binaries invigorate the stellar dynamo, giving rise to more active chromospheres.

5. Three years of continuous monitoring of Betelgeuse both in the UV and visible light revealed a periodic variation in the light of the star and a lag between the photospheric disturbances and the chromospheric variations, suggesting the presence of a propagating wave (Dupree et al. 1987). The results indicate that pulsation may be at work in heating and extending the atmosphere and driving the stellar wind. Identification of pulsation in luminous normal stars would be of interest for studies of stellar evolution. Certain regions of instability in the HR diagram, such as those of the Cepheid and long-period variable stars, have long been known. Pulsation may be more ubiquitous than previously thought.

6. The structure of the outer atmospheres of cool stars has been explored in detail through observations of binary systems in which such stars have hot companions (e.g. RS CVn–type systems and ζ Aur–type binaries). The cool-star atmosphere can be observed projected against the hot star at appropriate orbital phases. Some references on this topic are given in the section on close binary stars.

3. EVOLUTIONARY PROCESSES IN INTERACTING BINARIES

It has been estimated that two thirds or more of all stars are members of double or multiple systems. In addition, a large fraction of astrophysically intriguing objects, such as novae and X-ray binaries, involve binary systems. Hence, understanding the evolution in binary stars is important in understanding overall stellar evolution.

Mass flow in close binaries is thought to play an important role in evolution. The temperatures and densities of the flowing gas are such that the spectral signatures are most readily observable in the UV, particularly in the resonance absorption lines of singly or multiply ionized atoms, such as Mg II, Fe II, Al III, C IV, Si IV, and N V. Some metastable lines (e.g. those of Fe II and C III) have also proven valuable in providing information on the gas densities.

Gas flow is present in practically all close binaries observed by *IUE* in the high-spectral-resolution mode. Judging from the radial velocities of the absorption lines observed, a fraction of the gas is being lost from the binary. At the same time, a portion of the gas flowing out of the mass-losing star is apparently accreting onto the companion, as evidenced by high-temperature spectral features (such as Si IV, C IV, and N V) that would be too hot for single stars of the same spectral types.

Listed in the following sections are some of the significant results on close binary stars from the *IUE*.

3.1 *Discovery of High-Temperature Regions and Accretion*

IUE observations show high-temperature regions typically in terms of the absorption lines of highly ionized atoms such as Si IV, C IV, and N V in the case of Algol-type binaries. In the case of β Lyr, high-temperature lines are seen both in absorption and in emission (Hack et al. 1975). In Algol-type systems, the high-temperature regions are observed as absorption lines (Kondo et al. 1979, Peters & Polidan 1984). In W UMa–type binaries, the high-temperature regions are seen as emission lines of multiply ionized species (Rucinski 1985a). Rucinski (1985b) finds that the chromospheres of these binaries are exceedingly active, but that their coronal activities are less than those found in single stars. He also suggests that the gas in the common envelope in earlier type W UMa systems may escape because there are no magnetic loops to confine them.

Enhanced emission lines have been reported during and sometimes outside eclipse in a number of binaries, such as SX Cas and W Ser (Plavec et al. 1982, Plavec 1988), and have been attributed by Plavec (1988) to an accretion disk. Such lines were first observed in β Lyr (Hack et al. 1975). It is still not clear where such lines originate. The possibilities include the energized extended atmosphere of the mass-losing star, a plasma cloud extraneous to both of the stars, and an accretion disk.

The high-temperature absorption and emission lines cannot be accounted for simply in terms of the radiation field of the stars involved; they indicate the existence of a nonthermal energy source. In the case of the hot absorption features superposed on the B star in an Algol-type system, the high temperature is probably a result of accretion onto the B star.

3.2 *Mass Loss From Binary Systems*

The Doppler velocities in the short-wavelength-shifted absorption lines observed in most close binary systems indicate that matter is being lost from the systems. This indicates strongly that mass flow is not caused simply by the gravitational overflow from the critical Roche equipotential surface. Nongravitational forces must be responsible for propelling the gas out of the binaries (e.g. Modisette & Kondo 1980).

3.3 *Discovery of Hot Companions*

Due primarily to the efforts of Parsons (1981, 1983), hot companions have been found and studied in a number of binary systems. Of particular interest are HD 207739 and 22 Vul. The former contains an optically thick, variable gaseous envelope, and the latter is a short-period (249.083 days) ζ Aur–type binary with an atmospheric eclipse of the G3 supergiant star.

3.4 *Highlights of Work on Individual Binary Systems*

3.4.1 GRAVITATIONAL REDSHIFT DUE TO A NEUTRON STAR? V Sagittae, which was studied by Koch et al. (1986), exhibits emission lines with a constant redshift of 700 km s^{-1}. Since the redshift persists, it is difficult to explain it in terms of matter falling toward one of the components. One possible explanation is that the emission lines arise in the gaseous envelope surrounding a neutron star, and that the redshift is thus gravitational. If so, this is the first case in which a neutron star has been detected spectroscopically.

3.4.2 LARGE-SCALE STRUCTURES IN AN ACTIVE K DWARF. *IUE* observations of the eclipsing binary V471 Tau (K2 V+DA) revealed the three-dimensional structure of atmospheric loops and their associated starspots (Guinan et al. 1986). Just before and after total eclipse of the white dwarf component, when it is seen projected near the limb of the K dwarf, absorption lines such as C II, C III, C IV, and Si IV appear superposed on the continuum of the hot white dwarf. These lines probably arise in cool coronal loops overlying spots in the atmosphere of the K dwarf. Occasionally, a loop may extend almost one stellar radius from the K star.

3.4.3 DYNAMIC MASS FLOW IN U CEPHEI The Algol-type binary U Cep (B7–8 V+G8 III–IV) undergoes periodic episodes of extremely active mass flow, in which optically thick plasma engulfs the less evolved B component. Other binaries that involve optically thick plasma, which is concomitant to the short-lived dynamic mass flow phase, include β Lyr, R Ara, and HD 207739 (Kondo et al. 1985). Study of U Cep, which may be near the end stage of this phase, provides valuable information on what actually happens in this stage of binary evolution. During U Cep's latest active gas flow episode in 1986, high-resolution UV spectra were obtained for the first time. They showed that an optically thick plasma apparently emanating from the G giant covered much of the B companion, suppressing much of the UV flux from the hot star (McCluskey et al. 1988). Figure 1 shows the Mg II resonance doublet, in which gas streams were observed as multiple absorption features. Figure 2 shows an extremely broad absorption, due probably to overlapping multivelocity streams. Note that the flat bottom does not reach the zero flux level, indicating that the gas streams cover some 70% of the B-star hemisphere.

3.4.4 ADDITIONAL WORK ON BINARIES Further information on *IUE* results on close binaries is given by McCluskey & Sahade (1987). Additional reviews on this subject include those of Shore (1988), Sahade (1986), Rahe (1984), and McCluskey (1982). *IUE* observations have contributed significantly to the improved understanding of another category of binary systems, the cataclysmic variables, as shown by the role of *IUE* results in a recent IAU colloquium on cataclysmic variables (Drechsel et al. 1987). The reader is also referred to reviews on novae by Starrfield & Snijders (1987), on accretion onto compact objects by Cordova & Howarth (1987), and on eclipses of the extended atmospheres of supergiants by Hack & Strickland (1987). *IUE* work on RS CVn stars, another important subgroup of close binary stars, is reviewed by Catalano (1986).

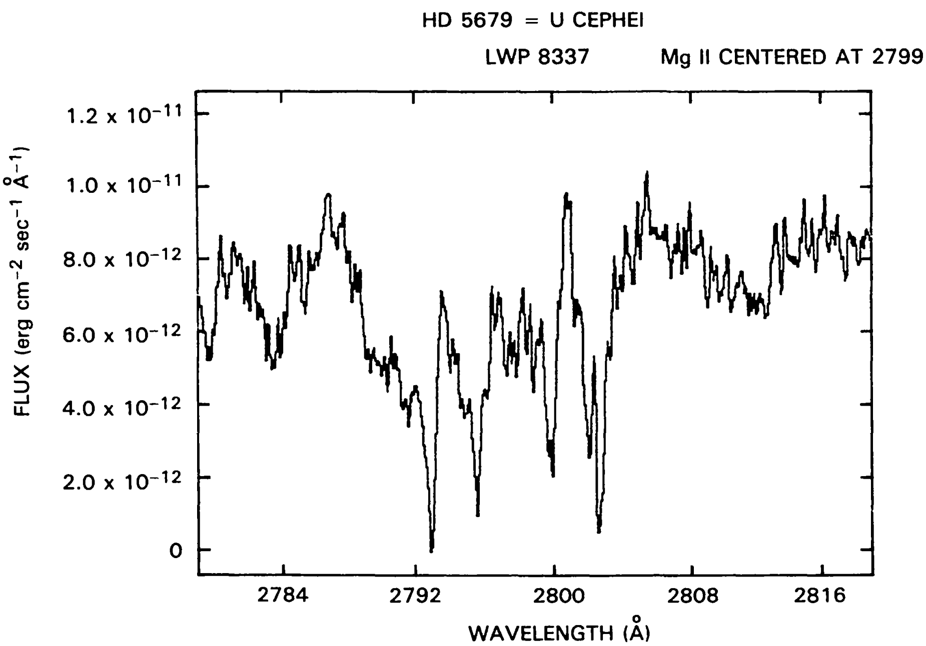

Figure 1 Mg II resonance doublet features of U Cep during a dynamic mass flow event (observation made on 4 June 1986). The rest wavelengths of the doublet are 2795.5 and 2802.7 Å. Multiple gas streams produce the numerous absorption lines at different velocities (McCluskey et al. 1988).

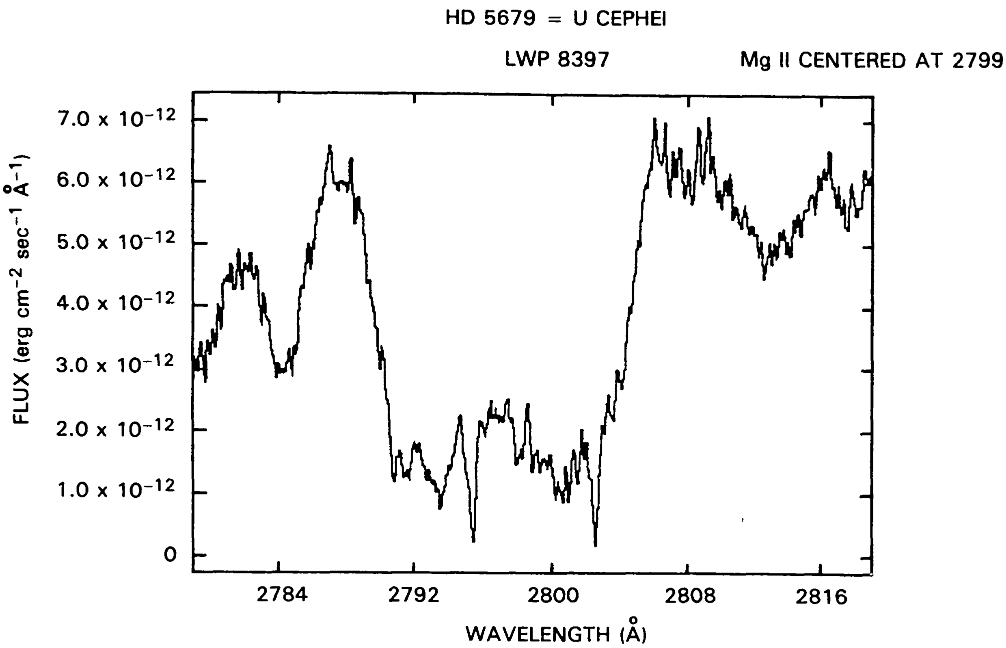

Figure 2 Mg II resonance doublet features in U Cep during the dynamic mass flow event of June 1986. This observation was made 10 days after that shown in Figure 1. The rate of mass flow has increased, and the numerous velocity components overlap to produce the appearance of an extremely broad absorption band (McCluskey et al. 1988).

4. WINDS FROM EARLY-TYPE STARS

IUE has contributed significantly to the investigation of winds in hot stars through its ability to reach much fainter stars than previous UV observatories. This has made a wider variety of stars accessible to observation, including the central stars of planetary nebulae and even the more luminous hot stars in a few galaxies of the Local Group, all with sufficient resolution to identify and measure wind components in spectral line profiles. The longevity of the spacecraft is also a major factor, for within the framework of an observatory administration that must allow for work in many other astronomical disciplines, it has enabled *IUE* users to (*a*) obtain spectra of literally hundreds of hot stars, allowing reliable inferences to be drawn about population properties and trends in wind properties with stellar characteristics; (*b*) make repeated observations of many stars, to establish and investigate variability in stellar winds; and (*c*) have enough time to design, propose, and execute new investigations in reaction to earlier *IUE* findings.

Inspection of reviews written at intervals over the first decade of *IUE* flight operations (e.g. Boggess & Maran 1980, Lamers 1980, Garmany 1984, Henrichs 1984, Kudritzki et al. 1986, Cassinelli & Lamers 1987, Willis 1988) shows how initial conclusions on the winds from hot stars based on *IUE* spectra were debated, reinforced, or revised as the observations continued. Early indications, for example, that the variation of wind parameters with stellar type is inconsistent with radiative driving gave way to a picture in which most workers are satisfied that radiative acceleration is at work. Initial evidence from *IUE* that the mass loss rates and wind terminal velocities are systematically lower in the OB stars of the Magellanic Clouds (LMC and SMC) than in corresponding stars of the Galaxy, presumably reflecting lower abundances of metals in the stars of the LMC and SMC, have also evolved. It is no longer clear that there are substantial differences in the mass loss rates when stellar types are accurately determined, but the differences in terminal velocities may be real.

4.1 *Winds in Extragalactic Stars*

Astronomers working with *IUE* have obtained UV spectra of hot stars and their winds in the LMC, SMC, M31, and M33. This subject was recently reviewed by Hutchings et al. (1987). The wind velocities are systematically lower in the observed OB stars of the LMC and SMC than in the Galaxy, and the intensities of the strong emission lines that drive the winds in the radiative acceleration model are also weaker. The differences are consistent with the trend of metal abundances, from highest to lowest: Galaxy, LMC, SMC. However, this simple picture clashes with the observation that OB supergiants in M31 and M33 also have weaker lines and slower winds than corresponding stars in the Galaxy. Also, in the Magellanic Clouds, it appears that the mass loss rates are not as small as predicted by the line-driven wind model (Garmany et al. 1988). Whether further progress demands nonradiative momentum transfer or simply more detailed consideration of the respective properties of individual stars remains to be seen.

4.2 *Winds in Planetary Nebulae Nuclei and Hot Subdwarfs*

Early *IUE* observations revealed the presence of strong winds in the central stars of planetary nebulae (Heap 1978). Subsequent work is reviewed by Köppen & Aller (1987) and Vauclair & Liebert (1987). The related discovery and follow-up work on winds in hot subdwarfs is reviewed by Willis (1988). Central stars of low-excitation and many hot-excitation planetary nuclei have fast winds; hot subdwarfs above some limiting luminosity appear to all have such winds. Reported terminal velocities for central stars and subdwarfs range from about 1000 to 5000 km s^{-1}, allowing them to be readily detected in low-dispersion *IUE* spectra.

Indicative of the extent of *IUE* investigations in this field, Cerruti-Sola & Perinotto (1985) report on a sample of 60 planetary nebula central stars. They found that the spectra of 42 stars had continua suitable for the detection of P Cyg profiles; of these, 22 stars actually showed such profiles. Analysis of the sample revealed that central stars with effective temperatures lower than about 63,000 K "almost always have a wind" and those with radii larger than 0.32 $R_\odot$ invariably have winds. Cerruti-Sola & Perinotto concluded that when the stellar surface gravity is below about $\log g = 5.2$, a planetary nebula central star always produces a wind.

The observation by *IUE* that high-speed winds are prevalent in central stars of planetary nebulae is widely interpreted as evidence for the colliding-winds theory for the origin of these nebulae, proposed in original form by Kwok et al. (1978).

4.3 *Stellar Winds and Stellar Evolution*

An especially significant result of the observations of stellar winds with *IUE* is increased knowledge of the dependence of mass loss rate on evolutionary state. Direct observational evidence of this phenomenon is crucial for progress in realistic calculations of stellar evolution. The review by Lamers (1980) reported that the rate of mass loss in young, massive stars seems to increase by two orders of magnitude from the main sequence to the hydrogen-shell-burning phase. Wolf-Rayet stars, which presumably are at a more advanced evolutionary stage, exhibit mass loss rates that may be still another order of magnitude greater. In these very luminous stars, this considerable increase in mass loss rate during evolution is accompanied by relatively little increase in the luminosity. Later, Garmany & Conti (1984) found that the ratio of the terminal wind velocity to the stellar escape velocity in O stars depends systematically on evolutionary condition. Specifically, near the zero age main sequence, this ratio is usually less than 3.0, while stars in which the velocity ratio is larger than 3.0 are usually evolved.

In a more recent review, Cassinelli & Lamers (1987) combine *IUE* data (which are available on many hot stars, but in which the derived mass loss rates are model dependent) with radio observations of a modest number of luminous hot stars, which yield the mass loss rate directly. They demonstrate that as massive stars evolve at nearly constant luminosity, the rate of mass loss increases with temperature and decreases with surface gravity. The data are fit by the relation

$$\log \dot{M} = -5.5 + 1.6 \log (L/10^6) - 1.0 \log (T/T_{\rm ZAMS}),$$

where $T_{\rm ZAMS}$ is the effective temperature of the star on the zero age main sequence.

5. THE INTERSTELLAR MEDIUM

5.1 *Earlier Studies*

Ultraviolet studies of the interstellar dust and gas were important objectives of several satellite projects and many rocket investigations prior to the *IUE*, and a great deal was learned about properties of the dust and gas that could be inferred from UV data. In particular, extinction was carefully studied with *OAO-2* and *TD-1* (Code et al. 1976, Nandy et al. 1976), and our understanding of the gaseous component was revolutionized by many fundamental results from *Copernicus*, such as the detection of O VI along many lines of sight (Jenkins & Meloy 1974), which led to a comprehensive new model of the interstellar medium (McKee & Ostriker 1977) consisting of a high-temperature, low-density substrate with scattered clouds that are at least partially ionized on the outside, but with cold interiors containing neutral material. *IUE*'s faint limiting magnitude has made possible refinements of this picture, as well as important improvements in our knowledge of the gas in the solar neighborhood and in the halo of the Galaxy.

5.2 *Survey Results*

In a high-resolution survey of OB stars, Shull & Van Steenberg (1985) measured H I column densities for 205 stars earlier than B2.5 and found the mean column density/r to be 0.46 cm^{-3}. This value is found to decrease for $r > 1$ kpc, perhaps owing to the effects of interarm gas. Van Steenberg & Shull (1988) have used the same survey to measure abundances of iron and silicon and find that both elements are substantially depleted (by factors of 10 to 1000), and that the depletion factor correlates with hydrogen column density, as one might expect if the heavy elements are being spent in grain formation in dense clouds. Substantial depletions have been measured along lines of sight encountering the ρ Oph cloud (Crutcher & Chu 1984) and the cloud toward HD 147889 (Snow & Joseph 1985).

5.3 *Local Interstellar Medium*

The local interstellar medium has been probed, using several types of stars as background sources. Spectra of nearby white dwarfs have been obtained for this purpose by Bruhweiler & Kondo (1981, 1982a) and by Dupree & Raymond (1982). White dwarfs are among the few nearby objects suitable for interstellar studies because they have strong continua, particularly in the UV, with very little photospheric structure to complicate the analysis. Consequently, column densities can be measured from features of N I, O I, Si II, C II, Fe II, and Mg II. Other studies have used nearby fast-rotating A and B stars (Frisch 1981, Bruhweiler & Kondo 1982b, Bruhweiler et al.

1984a,b, Freire Ferrero 1984, Skuppin et al. 1987) and late-type stars (Böhm-Vitense 1981, Drake et al. 1984, France et al. 1984, Vladilo et al. 1985). For both types of sources, data are obtained primarily using the Mg II doublet.

Although hydrogen densities cannot be measured directly, good values can be inferred from N I, which is known from *Copernicus* data (Ferlet 1981) to correlate closely with H I. Table 2 shows densities calculated for five white dwarfs, showing a strong anticorrelation between hydrogen density and distance. These data, taken together with *Copernicus* and backscattering results as plotted in Figure 3, indicate a high-density region (or cloud) in the vicinity of the Sun and Sirius B, with substantially reduced densities at greater distances. This picture is substantiated when Mg II data from the more numerous A, B, and late-type stars are considered. Genova et al. (1986) provide results for 91 cool stars, and 40% of them show no evidence of an interstellar feature.

Mg II data from stars within 25 pc indicate that the Sun is located near the outer edge of the Local Cloud, which is between us and the Galactic center. Lines of sight in the hemisphere toward the Galactic center show densities an order of magnitude higher than those towards the anticenter. As pointed out by Bruhweiler (1982), the location of this cloud correlates well with a dust patch discovered by Tinbergen (1982), who measured polarization in nearby stars. Values of N(Mg II)/N(Mg I) derived from *IUE* and *Copernicus* data for nearby stars indicate a temperature near the Sun of 7500–10,000 K (Bruhweiler et al. 1984a,b), consistent with the Sun's position near the edge of the cloud. On the other hand, Bruhweiler & Kondo (1982b) have found C I toward α PsA, in the direction of the polarization patch and Mg II concentration, which indicates a much lower temperature near the cloud center.

It is interesting that there is no evidence for any other cloud or high-

Table 2 Interstellar neutral hydrogen toward nearby white dwarfs

Star	d (pc)	log N(H I) (cm^{-2})	n(H I) (cm^{-3})
Sirius B[a]	2.7	17.93	0.087
W1346	13	18.04	0.024
HD 149499B	34	18.09	0.012
G191-B2B	48	17.92	0.006
Feige 24	90	18.30	0.008

[a] N I data are not available for Sirius B. Value deduced from average of Mg II and Si II.

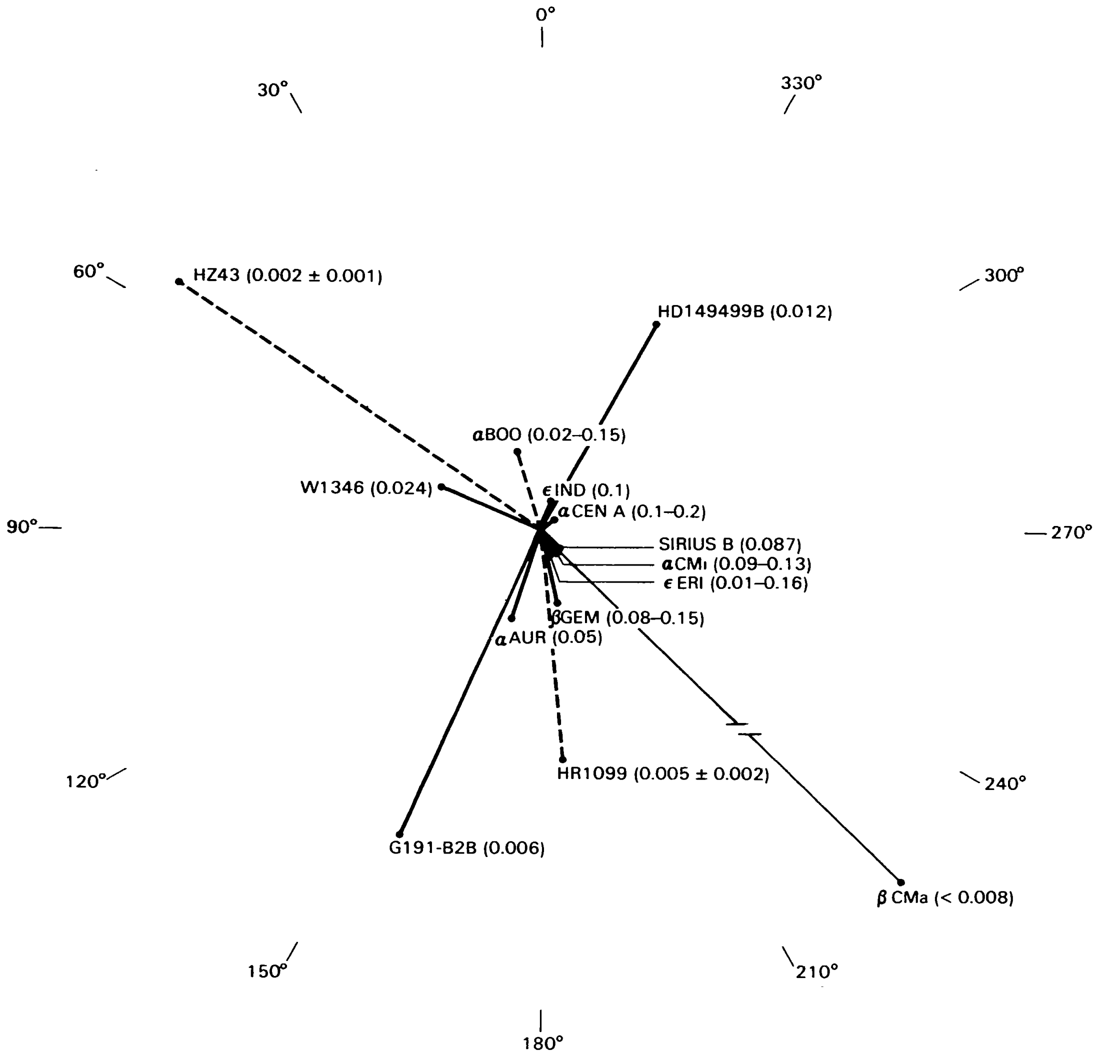

Figure 3 Average neutral hydrogen number densities toward nearby stars (Bruhweiler & Kondo 1982a). Vectors for each object lie in the direction of the object's Galactic longitude, with the length proportional to its actual distance. Dashed lines indicate paths with angles more than 45° out of the Galactic plane with lengths greater than 5 pc. Notice the dropoff in $\bar{n}_{\mathrm{H\,I}}$ at larger distances. The values for W1346 ($d = 13$ pc), HD 149499B ($d = 34$ pc), Sirius B ($d = 2.7$ pc), and G191-B2B ($d = 48$ pc) are from Bruhweiler & Kondo (1982a). The $\bar{n}_{\mathrm{H\,I}}$ value for HZ 43 is from the *Voyager* EUV experiment, while the other results are from *Copernicus*.

density feature within at least 50 pc of the Sun. This is in contrast with the McKee & Ostriker (1977) model, where the mean free path between cloudlets is about 12 pc. This may indicate either that the model needs modification or that the solar neighborhood is anomalous. Recent supernova activity in the solar vicinity may have evaporated many clouds.

5.4 *Interstellar Medium at High Galactic Latitudes*

One of the early discoveries of *IUE* was the existence of broad, strong absorption troughs due to C II and other species in the spectra of hot stars in the Magellanic Clouds (de Boer et al. 1978, 1980, Gondhalekar et al. 1980, Savage & de Boer 1981). These observations indicated that ionized gas existed to considerable distances above the Galactic plane and perhaps along the entire line of sight to the Magellanic Clouds. Subsequently, other lines of sight were explored using quasars at appropriate redshifts (York et al. 1984), extragalactic supernovae (Pettini et al. 1982, Jenkins et al. 1984), and high-latitude stars bright in the UV (e.g. de Boer & Savage 1984, Savage & Massa 1987).

Most of the material exists in neutral and low-ionization absorption systems that are found at distances of up to a few hundred parsecs above the Galactic plane. The gas exhibits metal abundances typical of interstellar gas in the solar neighborhood, and so it may be material that originated in the disk and was levitated by a Galactic fountain flow, as described by Shapiro & Field (1976), or by support from cosmic rays (Chevalier & Fransson 1984). It seems likely that it is also similar to the high-velocity clouds seen in 21-cm emission (van Woerden et al. 1985).

The more highly ionized gas shows a very different velocity distribution from the cool material and probably does not coincide with it. The C IV gas has a scale height of a few kiloparsecs (de Boer 1985, Savage & Massa 1987) and may result from the cooling of the hot, 10^6 K coronal material as well as from direct ionization due to cosmic rays and the short-UV radiation field. A few Magellanic Cloud stars have been analyzed to investigate abundances of the interstellar gas in the Clouds (e.g. Fitzpatrick & Savage 1983, de Boer et al. 1985). The depletion pattern is similar to that found in the Milky Way, but the overall abundance levels are lower, reflecting the lower metal content.

6. SUPERNOVA 1987A

The brightest supernova since Kepler's star of 1604 was discovered by Ian Shelton on 24 February 1987 in the Large Magellanic Cloud. Within three hours of notification of the discovery, *IUE* was pointed to the supernova in an existing target-of-opportunity program (Kirshner et al. 1987).

The first exposure showed that SN 1987A was extremely bright in the far UV. However, the UV flux declined rapidly hour by hour. Within three days, the far-UV flux, which was mainly from the exploding gas, declined by three orders of magnitude. Then, *IUE* observations revealed the spectra of two stars adjacent to the supernova. In readily available preexplosion photographs, only two stars were apparent. It was speculated that the progenitor was an unknown object and that since the exploding envelope was relatively thin, SN 1987A might be a Type I supernova involving a white dwarf and a companion.

However, careful analysis of a predetonation plate showed that there had really been three stars in the direction of SN 1987A. The supernova was still brightening in the visible range, and there was no way to take another plate from the ground to identify the missing star. The *IUE* spectra of the two remaining stars were examined by Sonneborn et al. (1987) at Goddard and by Gilmozzi et al. (1987) at Villafranca. They independently concluded that the star that disappeared was a blue supergiant. The high-resolution spectra obtained immediately after the discovery of SN 1987A proved invaluable also in the study of the interstellar media in the Milky Way, the Large Magellanic Cloud, and the intervening halo or haloes. We may never have such a bright UV background source available again for this purpose!

The *IUE* Fine Error Sensor (FES) used for tracking the target provided continuous coverage of the visual light curve of SN 1987A. The maximum brightness near magnitude 2.9 was attained three months after the explosion. An expanding gas cloud heated by radioactivity from isotopes created in the explosion accounted for the brightening. An exponential decline set in several weeks after maximum light. This was strong evidence that the radioactive decay of ^{56}Co to ^{56}Fe was then the main source of energy for heating the ejecta (Sonneborn 1988).

Several months after the explosion, high-temperature emission lines became observable in the far-UV. Detailed analysis of these features revealed that the emitting gas has an abnormal nitrogen-to-carbon ratio, which indicates that the composition of the gas was altered by nuclear processes inside the progenitor star prior to its release in a wind. These lines presumably arose in the gaseous shell formed by the stellar wind present in the red supergiant phase that preceded the immediate pre-supernova blue supergiant state. The lines were very narrow, which indicates that the expansion velocity of the emitting shell is less than 20 km s^{-1}, consistent with a red supergiant wind origin (Fransson et al. 1988). The brightness of the narrow emission lines peaked about 400 days after the supernova explosion. The radius of the circumstellar shell is therefore about 400 light-days or less.

7. ACTIVE GALACTIC NUCLEI

Prior to the launch of *IUE*, 3C 273 was the only active galactic nucleus that had been observed at UV wavelengths—first by the *Astronomical*

Netherlands Satellite (*ANS*; Wu 1977) and then by a rocket spectrograph of Davidsen et al. (1978). Since 1978, however, *IUE* has produced data on all types of active galactic nuclei (AGNs). Since it can only detect relatively bright AGNs (generally brighter than magnitude 17), observations have been restricted to low- to intermediate-redshift objects. Even so, *IUE* has played a valuable role in extending the wavelength range over which studies of the AGN spectrum can be made and in providing UV data for nearby, low-z sources to compare with ground observations of intrinsic UV spectra in high-redshift sources.

AGN spectra are characterized by a nonthermal continuum, usually ascribed to synchrotron emission, and broad emission lines. The emission lines are of two types: permitted resonance lines of abundant ions, many of which occur only in the UV, with Doppler widths of order 10,000 km s^{-1}; and forbidden lines with Doppler widths of order 1000 km s^{-1}. The continuum is thought to originate from a very small nucleus, perhaps powered by accretion. This nucleus is thought to be surrounded by a so-called broad-line region (BLR), of order 0.1 pc in diameter, that contains numerous high-density, high-velocity clouds that produce the broad, permitted emission lines. The BLR is supposedly surrounded by a larger narrow-line region where the forbidden lines originate.

Early efforts to understand the nonthermal continuous spectra of AGNs were complicated by attempts to intercompare data from low- and high-redshift objects based only on those wavelengths that were shifted into the bandpass of ground-based instruments. It was difficult to know if observed discrepancies were due to evolution effects, transmission effects in the intergalactic medium, or were intrinsic differences with wavelength. When it became possible to observe the spectra of individual sources over several decades of wavelength, from the UV with *IUE* into the far-infrared, it became clear that different phenomena dominate in the different wavelength regimes. In particular, many AGNs exhibit a so-called blue bump at wavelengths below 3000 Å (Oke & Zimmerman 1979, Oke & Goodrich 1981), which makes it impossible to describe the nonstellar continuum by a single power law. It now appears that this blue excess comprises most of the energy output for many AGNs.

For many AGNs the blue bump can be modeled satisfactorily by a single-temperature blackbody curve with $T = 26{,}000$ K (Edelson & Malkan 1986). Figure 4 shows the Malkan et al. (1987) model for the Seyfert 1 galaxy Mrk 335, indicating that the UV energy may be explained by a summation of the underlying power law, plus recombination radiation from BLR clouds and the 26,000-K blue-bump blackbody. In other sources the data can be fit better by models involving a geometrically thin, but optically thick, accretion disk (Malkan 1983).

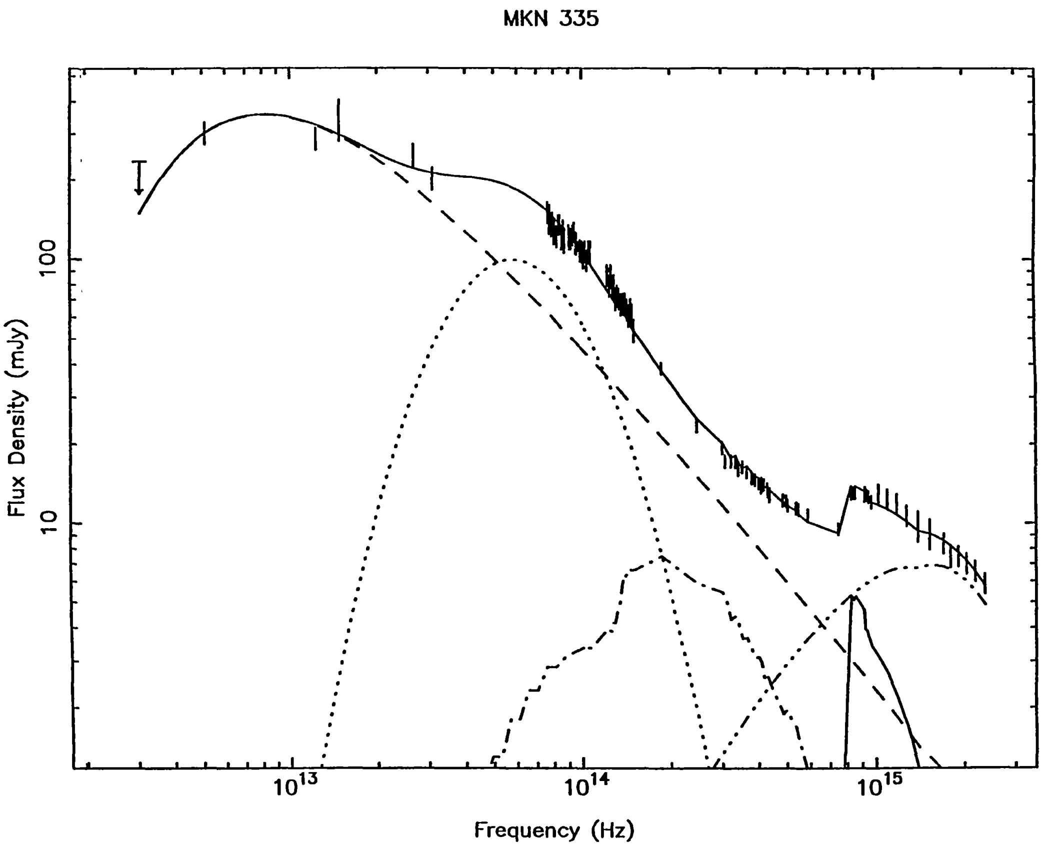

Figure 4 Decomposition of Edelson & Malkan's (1986) fit to the multiwavelength continuum of the Seyfert 1 galaxy Markarian 335. The dashed line is a power law with slope −1.2; the dot-dash line is the flux from starlight; the triple-dot–dash line is a blackbody with temperature 26,000 K; the short solid curve in the ultraviolet is recombination radiation from the BLR; and the dotted curve is a parabola centered at 5.8×10^{12} Hz with a FWHM of 3.3 octaves. Their sum is the long solid line, which fits the spectrophotometric data, shown by vertical error bars. From Malkan et al. (1987).

High signal-to-noise *IUE* spectra in the 2000–3000 Å region have revealed low-contrast structure due to the blending of many Fe II emission lines. These lines are so closely spaced that they can produce a pseudocontinuum containing an integrated flux comparable to that in Ly-α (Wills et al. 1985, Netzer et al. 1985). Models of the BLR clouds will have to be adjusted to allow for these unexpectedly high Fe II line fluxes.

Other UV results pose problems for modeling the BLR region: Although it is usually assumed that the broad emission lines are produced by photoionization because their strengths correlate well with the continuous spectrum, Baldwin (1977a) has pointed out that the C IV 1550-Å luminosity is anticorrelated with the nearby continuum at 1450 Å. *IUE* data were used to examine this relation over the full extent of AGN luminosities

(Wu et al. 1983), and it appears to hold not only statistically but also for individual sources as they vary in luminosity (Barr et al. 1983). Wu et al. (1983) suggest that the covering factor, or solid angle of the BLR clouds as seen from the nucleus, may be larger for less luminous AGNs; Malkan & Sargent (1982) suppose that the 1450-Å continuum radiation may not be proportional to the ionizing flux; and Mushotzky & Ferland (1984) suggest that the ionization parameter is larger in low-luminosity AGNs.

Measures of the Ly-α/H β intensity ratio are substantially less than should be expected from radiative recombination, as first pointed out by Baldwin (1977b). The average value of this ratio is 5 (Wu et al. 1980, Lacy et al. 1982), whereas the predicted value is 40. Examination of other Balmer and Paschen recombination lines suggests that the discrepancy is due to an enhancement of the Balmer series, which can give clues regarding the ionization structure of the BLR clouds (Kwan & Krolik 1981, Canfield & Puetter 1981).

A remarkable body of data has been assembled on NGC 4151, the nearest and brightest Seyfert 1 galaxy. Starting in the first year of *IUE* operations, a group of European astronomers pooled their observing time to obtain an extended series of observations on NGC 4151 in order to examine variability and other phenomena that could not be studied from isolated spectra of randomly selected sources. These data have been discussed by various groups (e.g. Penston et al. 1981, Bromage et al. 1985, Ulrich et al. 1985). In several Seyfert 1 galaxies, including NGC 4151 (Perola et al. 1982), luminosity variations have considerably larger amplitudes in the UV than in the visible or infrared. This may be due to the greater contamination by starlight at the longer wavelengths, which would reduce the apparent percentage of variation of the nuclear luminosity. Typical times for a doubling of the continuum brightness in NGC 4151 range from 5 to 30 days, implying a source size less than 0.01 pc. This is in contrast to X-ray flares, which can develop in less than 12 hr. It may be that the X radiation is more confined than the UV and optical radiation, possibly being produced by a different mechanism.

The temporal variations of the continuum and emission lines in the Seyfert galaxy Fairall 9 were observed with *IUE* and with visible and infrared instruments. The results show clearly that there is a time lag between maximum light in the continuum, which presumably arises in the inner part of the accretion disk surrounding the putative supermassive black hole, and maximum light in the lines, which are supposed to originate from the outer regions of the disk. The UV and visible light emission lines reached maximum 155 days after the UV continuum maximum, while the IR lines peaked at 400 days after UV continuum maximum. The time lags yield information on the width and physical properties of the accretion disk (Clavel et al. 1989).

The bright, high-redshift ($V = 16.1$, $z = 2.72$) quasar HS 1700+6416 was observed with *IUE* by Reimers et al. (1989) at low and high resolution to yield the first information on a quasar at rest wavelengths as short as 330 Å. Although intergalactic Lyman-line and continuum absorption depresses the continuum significantly between rest wavelengths 850–450 Å, the continuum rose sharply toward shorter wavelengths to at least 330 Å. If this result applies to other quasars and AGNs, the continuum maximum probably lies beyond about 300 Å.

8. SOLAR SYSTEM OBJECTS

The *IUE* has been used to study solar system objects, including planets, natural satellites, asteroids, and comets. These observations are challenging from the point of spacecraft operations, as these objects show motions relative to the inertial frame. Among the planets studied are Venus, Mars, Jupiter, Saturn, and Uranus (Moos & Encrenaz 1987). The planetary satellites observed are the Galilean satellites of Jupiter (namely Io, Europa, Ganymede, and Callisto) and four large satellites of Saturn (namely, Tethys, Dione, Rhea, Iapetus; Nelson & Lane 1987). Observations of the remarkable Io torus and its interactions with the Jovian magnetosphere were recently reviewed by Ballester et al. (1988).

Over two dozen comets have been observed with the *IUE* (Festou & Feldman 1987). Observations of Comet IRAS-Araki-Alcock were particularly noteworthy. The comet came within 5×10^6 km of the Earth, which made the tracking quite a challenge but which also made the point-like circumnuclear region a bright object at closest approach. The unexpected discovery of the sulfur dimer emissions in the far-UV spectrum of this comet is one of the most significant cometary results of the *IUE* (A'Hearn & Feldman 1985). A systematic record of the varying UV emissions of Comet Giacobini-Zinner allowed *IUE* to support the first intercept of a comet, the visit of the *International Cometary Explorer* (*ICE*) to that object (McFadden et al. 1987). *IUE* made the most extensive space-based telescopic observations of Comet Halley during its sweep through the inner solar system in 1985–86. The *Challenger* accident prevented the planned March 1986 launch of the UV *Astro* mission payload, and *IUE* accordingly became the workhorse UV support facility as several interplanetary probes (ESA's *Giotto*, Japan's *Sakigake* and *Suisei*, USSR's *Vegas 1* and *2*, and USA's *ICE*) flew through or past the comet. *IUE* observations of the OH emission from Comet Halley showed that it was ejecting several tons of water per second near its perihelion passage (Rahe 1988).

9. OTHER TOPICS

There are 31 chapters on distinct research topics in the compendium *Exploring the Universe With the IUE Satellite* (Kondo et al. 1987), but even those chapters were too few to portray the full scope of the astrophysical research performed with this satellite observatory. Likewise, some of the themes not covered in this review include symbiotic stars (Nussbaumer & Stencel 1987), intrinsic variable stars (Böhm-Vitense & Querci 1987), pre-main-sequence stars (Imhoff & Appenzeller 1987), white dwarfs (Vauclair & Liebert 1987), interstellar dust and extinction (Mathis 1987), supernovae and their remnants (Blair & Panagia 1987), H II regions (Dufour 1987), starburst galaxies (Kunth & Weedman 1987), globular clusters (Castellani & Cassatella 1987), blazars (Bregman et al. 1987), and quasar absorption lines and galaxy haloes (Bergeron et al. 1987).

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