

Ultraviolet astronomy enters the eighties

A decade of observations by Earth-orbiting satellites has led to the discovery of compact, hot components in many stellar systems and extended coronas surrounding our Galaxy and others.

Stephen P. Maran and Albert Boggess III

Ultraviolet astronomy, once the province of instrumentalists, has become an accessible and necessary technique for all astronomers. In the first three years after the 1972 launch of the *Copernicus* satellite about 100 astronomers used its ultraviolet-spectrometer data, outnumbering by a factor of ten the core group of Princeton University scientists who superintended the instrument. In the first two years of observational programs with the most recent ultraviolet satellite, the International Ultraviolet Explorer (IUE), this involvement of non-experimenters has mushroomed, with more than 500 scientists participating.

The most recent findings obtained with the IUE and other ultraviolet spacecraft include the following:

- ▶ Hot components—compact stars and various circumstellar plasma distributions—are found in association with a wide variety of stellar objects, from stars in the making to highly evolved red giants.
- ▶ Stellar winds occur in stars of many types, with wind properties perhaps connected with stellar magnetism.
- ▶ The strength of ultraviolet emissions from the outer atmospheres of cool stars may be linked to stellar rotation rates (and, by implication, to stellar magnetism).
- ▶ The Milky Way Galaxy and other galaxies possess hot coronas.

Electromagnetic radiation in the wavelength range associated with ultraviolet astronomy (roughly 100–320 nm) is strongly absorbed by the Earth's atmosphere. Therefore, observations have been conducted from platforms placed above at least a large part of the

atmosphere—high flying experimental aircraft, balloons, sounding rockets, Earth-orbiting satellites, the lunar surface (during the *Apollo* missions), and interplanetary spacecraft.

Historical development

Ultraviolet astronomy began with sounding-rocket experiments shortly after World War II. Rockets are still very useful to test new instruments, detectors, and control techniques—as one can see, for example, from the very sharp ultraviolet photo of Messier 33 shown in figure 1—but the bulk of the astronomical work is now done by satellite observatories, with the emphasis on high-resolution spectrometry. The first major ultraviolet satellite, *Orbiting Astronomical Observatory-2*, made a photometric reconnaissance of the solar system and ultraviolet sources within the Galaxy and measured a few dozen bright nearby galaxies. Subsequent European spacecraft extended photometry to more and dimmer stars and obtained low-dispersion spectra of a variety of objects.

The next major American craft, *Copernicus*, carried both ultraviolet and x-ray instrumentation. Observations made with *Copernicus*'s ultraviolet spectrometer, the brainchild of Lyman Spitzer Jr. (Princeton University), revealed the existence of a hot, thin phase of the interstellar medium in the galactic plane and led to the determination of the isotopic abundance of deuterium along many paths through the Galaxy. Useful information continues to emerge from studies using the now-aging satellite.

The IUE, launched early in 1978, is a joint enterprise of NASA, the European Space Agency and the UK Science Research Council. The first astronomical research satellite to be placed in geosynchronous orbit, it remains in continuous communications with the ground controllers at Goddard Space

Flight Center (GSFC) in Greenbelt, Maryland. Observations are conducted at "telescope-operations centers" at GSFC and at Villafranca, Spain, near Madrid.

Earlier satellites were limited in their observations by the large solid angle of the Earth as seen from low Earth orbit. The Earth is only about 17° in diameter as seen from IUE, so that randomly selected celestial targets are more likely to be accessible at any given time and are occulted by the Earth over shorter intervals than from low Earth orbit.

Using the IUE, the ultraviolet astronomer can inspect observations immediately after they are performed and can modify the observing program in response to the results. It is also feasible to react quickly to newly discovered "targets of opportunity"—comets, supernovae and other transient celestial phenomena reported by other observatories. Indeed, proposals are on file not only for regularly scheduled observations, but also for the various classes of transient events.

The IUE's essential observing equipment consists of two ultraviolet echelle spectrographs, each provided with two observer-selectable entrance apertures and two spectral-dispersion modes. The wavelength ranges of the spectrographs are 115–195 nm and 190–320 nm, respectively. The detectors are electronic image converters that are optically coupled to secondary-electron conduction (SEC) vidicon cameras. The vidicons make it possible to take time exposures of the spectra. Exposure times on faint targets are limited by particle radiation hits, which eventually saturate the target of the SEC vidicon. Under exceptional conditions, useful exposures on faint extragalactic objects have been obtained with durations of up to 15 hours.

An astronomer at GSFC or Villafranca operates much as one would at a

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Ultraviolet photo of M33 ($\lambda_{\text{eff}} = 200 \text{ nm}$, $T_{\text{exp}} = 20 \text{ sec}$) taken through a 33-cm telescope carried aboard an Astrobee sounding rocket in October 1979. The galaxy's spiral arms are shown more

clearly than in visible-light photographs (note the prominent clouds of ionized hydrogen and groups of young, massive stars). (Courtesy of Ralph Bohlin and Theodore Stecher, NASA-GSFC.) **Figure 1**

major ground-based facility. The observer sees a TV-displayed white-light image of the field of view through the 0.45-m IUE cassegrain telescope and uses field charts or Polaroid enlargements of portions of the Palomar Observatory Sky Survey (for example) to recognize target and guide stars. Pointing corrections are made, and the spectrograph exposure begins. When the exposure is completed, the ultraviolet spectrum is displayed on the TV screen. (Hard copies and computer-compatible magnetic tapes are provided for later analysis.)

The IUE design, performance and early results are described in the 5 October 1978 issue of *Nature* (reference 1 and accompanying papers). The most recent of four symposia devoted to IUE studies was held at GSFC on 7-9

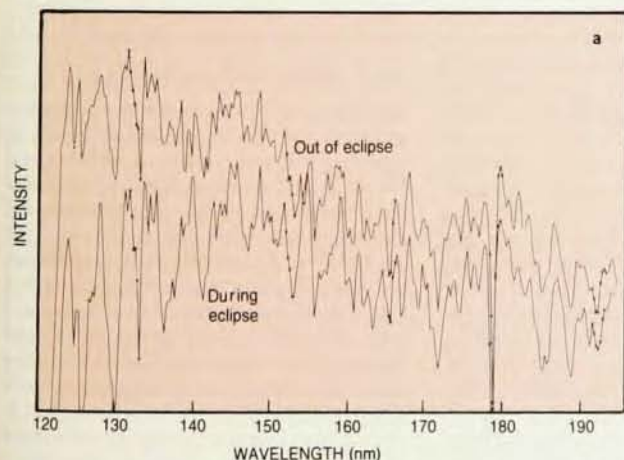
May 1980. Most of the results described here are presented or referenced in the proceedings of that conference and an earlier one.^{2,3}

Finding hot components

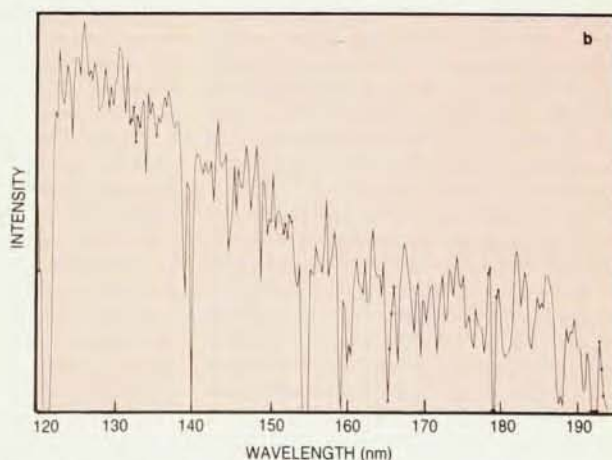
Stars are classified by their visual spectra. In a binary system, if the visual magnitudes of the two stars are comparable, spectral features of each are discerned in the visual-light spectrum and can be classified. If one star has a much brighter visual magnitude than the other, only a single set of spectral lines is seen; one knows that the lines arise from a member of a binary system when cyclic Doppler shifts due to orbital motion are observed. If a bright star has a hotter, much smaller companion, such as a white dwarf, the hot star will dominate

the short-wavelength emission from the system. The Sirius system provides a striking example of this phenomenon (although in this case the two stars are spatially resolvable). The primary, a 10 000-K main-sequence A star, has the brightest apparent visual magnitude of any star in the night sky, but *Copernicus* observations by Malcolm Savedoff (U. of Rochester) show that the faint white-dwarf companion is brighter at wavelengths below about 110 nm. Figure 2 shows how the spectrum of a hot companion can be isolated when the system is an eclipsing binary.

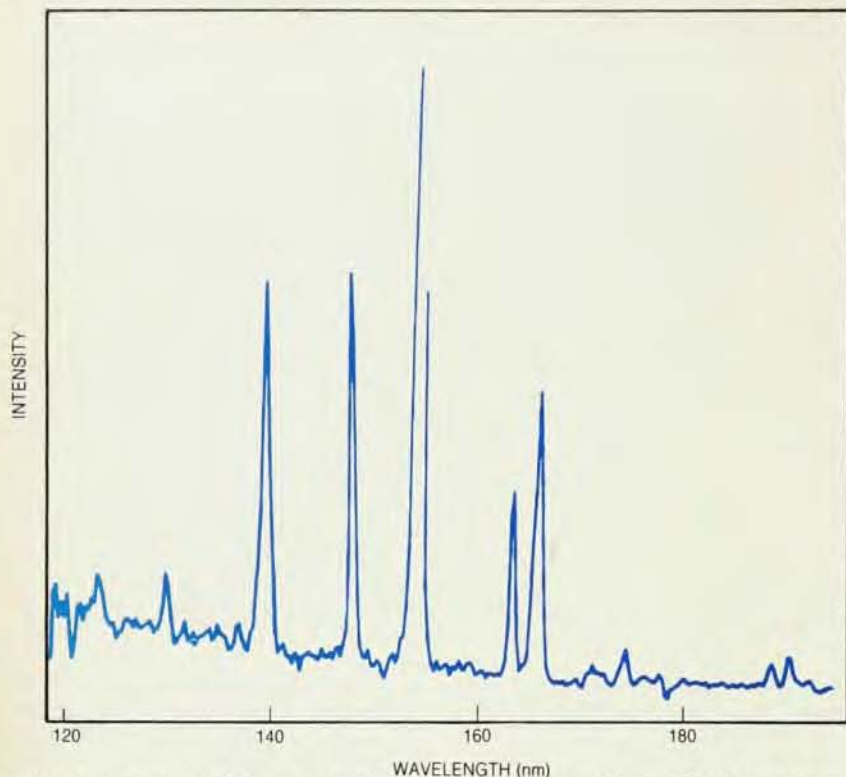
IUE users have found hot components in a variety of binary systems, including some companions to stars not generally suspected of being binaries. Among the latter are two of the Cepheid variables, the well-known class of



Previously unobserved hot companion of a type-B8 supergiant, μ Sagittarii, an eclipsing binary, was discovered by comparing in-eclipse and out-of-eclipse spectra of the system obtained using the International Ultraviolet Explorer. Plot (a) shows the two observed spectra;



plot (b) gives the subtracted spectrum of the hot component, believed to be a main-sequence type-O star with an effective temperature of 40 000 K. (Courtesy of M. Plavec, UCLA, with eclipse data from E. F. Guinan and E. M. Sion, Villanova U.) **Figure 2.**



Ultraviolet emission lines from RW Hydrae, a symbiotic star whose visible-light spectrum marks it as a red giant, indicate the presence of a small photo-ionized nebula. The continuum seen rising toward the shorter wavelengths has been interpreted as radiation from a compact companion star with effective temperature $T \geq 10^5$ K. (Courtesy of Andrew Michalitsianos, NASA-Goddard Space Flight Center.)

Figure 3

cool pulsating stars whose well-calibrated relation between pulsation period and absolute luminosity makes them useful as distance indicators. John Mariska, George Doschek, and Uri Feldman (Naval Research Laboratory) examined six Cepheids and found that two, η Aquilae and T Monocerotis, have ultraviolet spectra that remain constant (at wavelengths below 160 nm for η Aql and below 260 nm for T Mon) as the stars pulsate and their visual magnitudes change. The investigators interpret the steady ultraviolet emission as arising from main-sequence stars with effective temperatures of about 10 000 K, so that the faint, hot companions of the two Cepheids are stars resembling the cool, bright primary of the Sirius system!

In another case, the newly discovered hot companion resembles the white dwarf Sirius B. Erika Bohm-Vitense (University of Washington) identified the new white dwarf in the ultraviolet spectrum of ζ Capricorni, a type-G5 giant belonging to the class of Ba II stars (cool giant stars that exhibit abnormally strong absorption lines of singly ionized barium in their visual spectra). Bohm-Vitense's finding supports a recent suggestion that the apparent excess of barium in the atmospheres of these giants may result from mass exchange with companion stars, rather

than from mixing processes within the giants themselves.

Symbiotic systems

The existence of hot companions in a particular class of stars, the "symbiotic" stars, has been suspected for many years. These objects appear to be red giants, but their visual spectra contain indications that hot continua are exciting emission lines in circumstellar material. Thus, it is not very surprising that the IUE spectra of some symbiotic stars reveal what may be ultraviolet continua of companion stars (figure 3). Some of these objects have been described as white dwarfs, but according to Mirek Plavec, they actually are hot helium subdwarfs (a type of star thought to be intermediate between white dwarfs and the central stars of planetary nebulae). Nuclear burning is underway within a helium subdwarf, but not inside a white dwarf, which explains why the subdwarfs may be much more luminous. Some symbiotic-star spectra show an additional ultraviolet continuum, ascribed to free-free and bound-free radiation from hydrogen. The hydrogen is usually interpreted as matter ejected from the red giant and photo-ionized by the white dwarf.

A few astronomers doubt that symbiotic stars even have hot secondaries,

arguing instead that they are red giants whose atmospheres are gradually detaching, eventually to become planetary nebulae. Direct radiation from the hot core—essentially a helium subdwarf—of the disrupting red giant could account for some of the ultraviolet observations. A third possibility is that the high-temperature material is located in a large, strongly magnetized "star spot" on a red giant.

Supporters of the binary hypothesis for symbiotic stars outnumber the single-star advocates, but they are faced with a number of interesting problems. It has been widely assumed that the white dwarfs are accreting gas derived from the red giants, but the red giants do not appear to be filling their Roche lobes, which (by conventional theory) means that only stellar winds can transfer mass to the secondary stars. Symbiotic systems are not close binaries, so the white dwarfs intercept only negligible fractions of the winds from the primaries. Various astrophysicists have speculated that tidal interactions, heating of the primary star's atmosphere by radiation from the white dwarf, or even guided flow along magnetic field lines may enhance mass transfer, but a cogent theory has not yet been offered.

An interesting alternative has emerged from an analysis of line profiles in the ultraviolet spectrum of the symbiotic star AG Pegasi by Plavec and Charles Keyes (both at UCLA). They found that emissions from highly ionized gas (presumably located very close to the hot star) have line profiles that indicate rapid outflow. (In such "P-Cygni" profiles, a conspicuous absorption feature is located on the short-wavelength side of a broad emission line, as shown, for example in figure 4.) This means, says Plavec, that theorists should look to the small companions, rather than to the red giants, as the likely sources of the distributed plasma in symbiotic binary systems.

What makes the winds blow?

A new view of the outer atmospheres of stars and their associated winds is emerging from space observations. Work with the EINSTEIN x-ray observatory by Giuseppe Vaiana (Center for Astrophysics) and associates has revealed that hot stars of all types have significant x-ray emission, indicating the widespread presence of hot coronas. The IUE, like *Copernicus*, is used to study the winds associated with the coronas. The winds are recognized by P-Cygni profiles (figure 4) and, where P-Cygni features are lacking, by certain kinds of absorption-line profiles.

A recent review⁴ notes three general classes of wind mechanism:

► radiation pressure communicated by resonant scattering in atomic lines,

► energy derived from magnetic phenomena and wave motions in the atmospheres, and

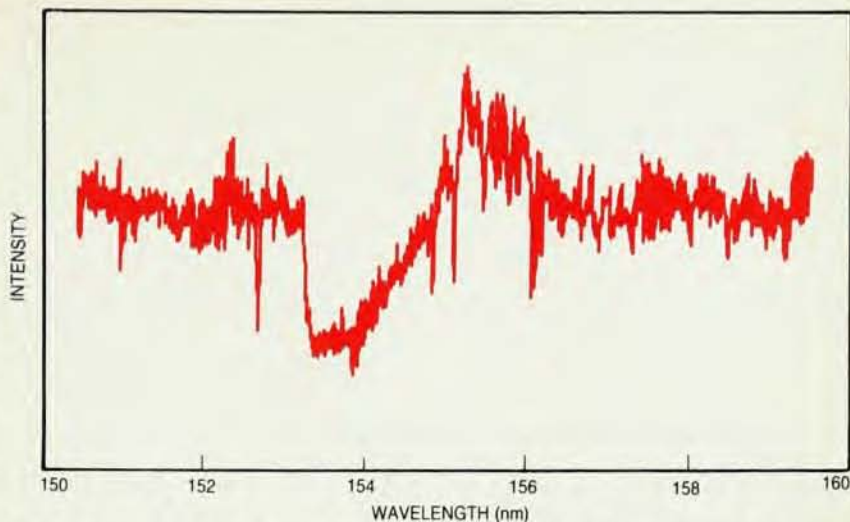
► radiation pressure on dust grains that form in cool expanding atmospheres.

It has been widely thought that these processes are important, respectively in the hot, massive, "early-type" stars; in many of the cooler, "late-type" stars, such as the Sun and red giants, and in red supergiants.

The International Ultraviolet Explorer extends the studies initiated by *Copernicus* to more distant and numerous stars, enabling observers to seek systematic patterns and differences. This has resulted in serious challenges to the first class of wind model mentioned above. Peter Conti and Catharine Garmany (Joint Institute for Laboratory Astrophysics) recently studied 16 O-type main-sequence and giant stars with IUE. According to the popular theory of radiation-driven winds for such objects, there should be a linear relation between the bolometric magnitude and the logarithm of the mass-loss rate in the wind. Previous work on more luminous types of O stars appeared to show just such a relation. However, Conti and Garmany find substantial, physically real scatter in their survey; O stars of equal luminosity may differ by a factor of 30 in mass flux, suggesting that an additional process may contribute to driving the winds, or that a more complex variation on the current theory is required.

It appears that a luminosity threshold exists that a hot star must exceed to possess a detectable stellar wind. The threshold, at bolometric magnitude -6, has been previously recognized among the hottest stars. Now Henny Lamers (at the Astronomical Institute, Utrecht) has expanded the survey of winds in early-type stars to cooler objects and finds that the same threshold applies all the way from O-type stars with effective temperatures of close to 40 000 K to late A-type stars cooler than 8000 K.

There is, however, a basic exception to the threshold rule: Fast-spinning stars, with $v \sin i > 200$ km/sec (where i is the inclination of the spin axis to the line of sight), can be dimmer than $M_{bol} = -6$ yet still produce observable winds. Lamers notes that the real trend in stellar mass loss is not a systematic increase with luminosity, but rather an increase in mass-loss rate with the evolutionary state of the star: Hot stars that have evolved off the main sequence lose mass more rapidly than objects of the same mass still on the main sequence. He takes this as evidence against radiation-driven wind models and infers that the mass-loss mechanism must depend on the state of the stellar interior, where evolution is



Well-developed P-Cygni structure appears in the ultraviolet spectrum of the luminous, evolved type-O star HD 46150. Note the strong absorption line at the short-wavelength side of the prominent emission line (154.8 nm, 155.0 nm resonance doublet of triply ionized carbon). One can estimate the terminal speed of the stellar wind from the steep short-wavelength edge of the absorption feature. (Courtesy of Peter S. Conti and Catharine D. Garmany, Joint Institute for Laboratory Astrophysics.)

Figure 4

driven by progress in nuclear burning.

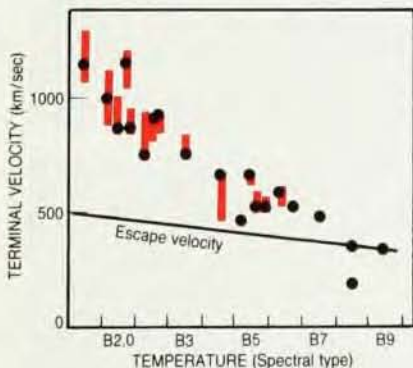
Anne Underhill (GSFC) suggests that the coronas of early-type supergiants, which are hotter than theorists had anticipated, provide an important clue to the mechanism that must supplement or dominate radiation-driven winds. She believes these coronas are heated by the same class of magnetodynamic processes that apparently account for the high temperature of the solar corona. Simple scaling from a model recently proposed for late-type stars (in which magnetic phenomena are generally taken for granted) appears to account for the observed decreases in ionization level and mass-flow rate of the coronas and winds among supergiants from late O-type

(effective temperatures around 26 000 K) to early A-type (10 000 K) stars.

On the Sun, eruptions and other active phenomena are intimately related to magnetic processes. It is generally believed that solar flares, for example, represent the sudden release of magnetic energy stored in localized volumes over extended periods.

Underhill's suggestion, appropriately elaborated, might apply to another phenomenon of stellar winds that has been intensively examined by means of the IUE—their pronounced time-dependence. Earlier studies with *Copernicus* and an ultraviolet balloon-borne spectrometer called BUSS led Lamers to suggest that the winds of hot stars may come in sporadic puffs rather than in steady streams. IUE confirms that puffs indeed are common. In one particularly noteworthy star, γ Cassiopeiae, high-velocity (~1500 km/sec) wind lines seem to come and go, typically lasting only about a week. The puffs, not easily explained by a simple radiation-driven wind model, could obtain at least their initial impetus from coronal or chromospheric eruptions whose energy is derived from magnetodynamic effects. Alternatively, puffs might be produced by rotational modulation of regions of preferred mass-loss on the star. The latter might be analogous to the high-speed streams in the solar wind that are controlled by the distribution of coronal holes (regions of open magnetic field lines) on the Sun.

Radiation may still play an important role in the acceleration of stellar-wind material. One cogent argument for a radiation-pressure contribution to the winds, says Joseph Cassinelli (University of Wisconsin), is an observed



The terminal velocities of stellar winds in B-type supergiants decline much more rapidly with decreasing photospheric temperature than does the escape velocity. Dots represent velocities measured from Si IV lines; boxes enclose results from measurements of lines of several ions for single stars. The data were all obtained with IUE by Joseph Cassinelli and David Abbott.)

Figure 5

decrease in the ratio of v_{∞} (the terminal, or highest attained velocity in a wind) to v_{esc} (the escape velocity), as illustrated in figure 5. The ratio decreases from 3 for O-type supergiants to 1 or less for A-type supergiants, contrary to the idea that stars must be taken as individuals whose winds cannot be predicted from gross parameters of mass and radius. However, observations of mass loss in an evolved hot star of the Wolf-Rayet type (γ Velorum) by Allan J. Willis (University College Lon-

don) reveal that the momentum in the wind exceeds that in the radiation by a factor of 90. Clearly, much more effort is required to elucidate the wind mechanism in hot stars.

Cool stars—a hot topic

One of the most hotly debated and rapidly developing areas of ultraviolet astronomy has been the study of late-type stars. At issue has been whether or not there are well-defined regions of the Hertzsprung-Russell Diagram

(physically this is the effective-temperature-absolute-magnitude plane, it is often plotted in terms of absolute visual magnitude *versus* spectral type of stars) that correspond to the loci of stars with and without certain features of the outer atmosphere, such as a corona or a wind. Magnitudes and spectral types generally are defined in terms of the stellar properties observed in visible light, so that they correspond to the photospheric parameters of the stars. Are these param-

Seeing an eclipsing binary with the IUE

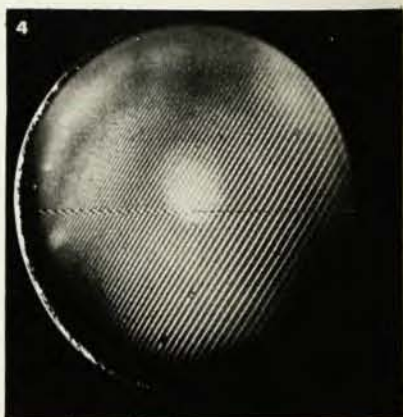
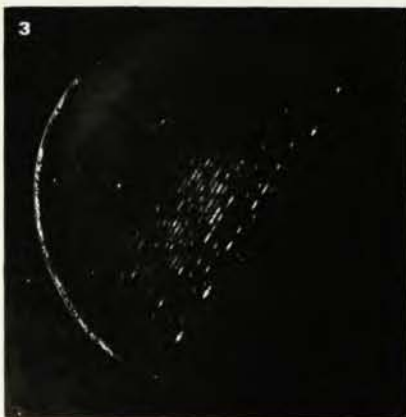
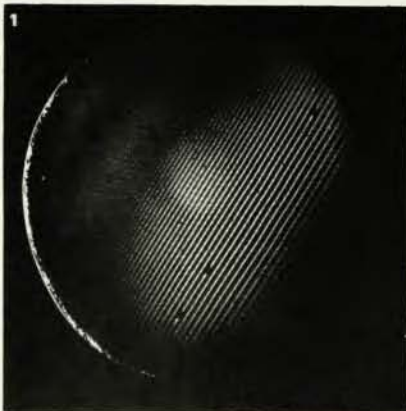
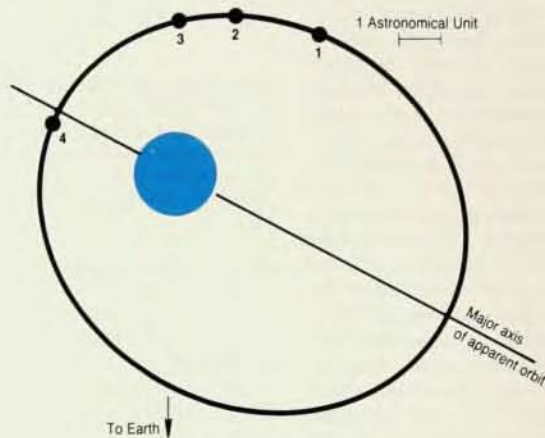
The sketch at top depicts the ζ Aurigae system (a so-called "atmospheric" eclipsing binary), showing the apparent orbit of a hot, main-sequence B8 companion about the primary star, a cool red supergiant. The size of the primary and the diameter of the smaller star's orbit are drawn to scale. Marks on the orbit correspond to positions of the B8 star when spectrograms 1, 2, 3, and 4 were obtained by Robert D. Chapman (NASA-GSFC) using the IUE. Dramatic changes in the system's ultraviolet spectrum may be seen in this sequence of high-resolution spectrograms.

Each spectrogram covers a range of wavelengths from 190 to 320 nm, with echelle orders (diagonal streaks) arranged so that wavelengths increase from top left to bottom right; along an individual order, wavelength increases from right to left.

In Spectrogram 1, obtained on 15 September 1979, the B8 star has not yet entered eclipse. Its bright continuum dominates the figure, but some absorption features (dark lines or bands) can be seen. Most conspicuous are two dark bands on the left side of a single echelle order (lower center), the h and k lines of singly ionized magnesium. These two lines show clear "P-Cygni" profiles; Chapman calls them the signatures of a cool, circum-system shell expanding at about 100 km/s and supplied by a wind from the supergiant.

Spectrogram 2 (18 November 1979) shows an enormous increase in the number of absorption lines. The B8 companion is shining through the extended atmosphere of the supergiant from behind, and nearly all of the lines (about half of which are due to singly ionized iron) are produced in the supergiant's atmosphere. The h and k lines visible in Spectrogram 1 can still be seen. Spectrogram 3 was taken at mid-eclipse (16 December 1979), with the B8 star entirely hidden. We now see emission lines from the supergiant, and the bright ultraviolet continuum from the hotter star has vanished—the effect is one of bright bands on a dark field, in place of the dark bands on a bright background seen in Spectrogram 2. At 300 nm, the supergiant's emission continuum is about 5% as strong as the pre-eclipse continuum, dominated by the B8 star.

The spectrum shown in Spectrogram 4 (29 February 1980), with the B8 star well outside of eclipse again, resembles that seen in Spectrogram 1.



eters uniquely related to the existence and characteristics of the outer atmospheric regions?

Jeffrey Linsky (JILA), leader of one of the active groups in this field, describes the Sun as a useful prototype for many of the stars on the H-R Diagram: Above the solar photosphere are the chromosphere, the geometrically thin transition region, a hot corona ($T \sim 10^6$ K), and a low-mass-flux ($\sim 10^{-14} M_{\odot}/\text{yr}$) wind. Stars resembling the Sun in having hot coronas and weak ($< 10^{-10} M_{\odot}/\text{yr}$) stellar winds range along the main sequence from early F-type stars to the coolest known red dwarfs. G-type and early K-type giants also appear to share these characteristics.

In 1979, based on the early IUE results on about 20 stars, Linsky and Bernhard Haisch (Lockheed Palo Alto Research Laboratory) claimed to have discovered a sharp dividing line on the H-R Diagram between stars that have a "solar-type" outer atmosphere and "non-solar" stars that have 10 000–20 000-K chromospheres but no transition regions or coronas. This was taken as supporting a suggestion that in supergiant stars the occurrence of massive winds ($> 10^{-8}$ solar masses/yr) prevents formation of a corona. The existence of such a dividing line was questioned by members of a group at the Center for Astrophysics in Cambridge, Mass. Lee Hartmann and Andrea Dupree of the Cambridge team point to the existence of "hybrid" supergiants such as α and β Aquarii, which have both high-temperature outer atmospheres (~ 200 000 K) and massive stellar winds.

Present information indicates a general weakening of transition regions and coronas as one goes to cooler stars among the red giants and supergiants, with what Dupree has termed an "intermediate region" between stars with hot coronas and weak winds and those without coronas but with cool, massive winds. Tom Ayres of the JILA group explains that the "sharp division" was an artifact of selection effects in the early IUE observations.

Going toward the hotter, A-type stars in the H-R Diagram theorists have generally anticipated that the solar-type outer atmospheres would vanish, because models indicate that the convective zones of A stars are thin and hence provide little mechanical energy to heat the outer layers. But EINSTEIN measurements show that A stars indeed have hot coronas. Various workers currently are examining possible heating mechanisms. A separate question is what drives the cool, massive winds of the luminous red giants that lack coronas. Gibor Basri (University of California, Berkeley) notes that as yet no consistent theory has been estab-

lished for chromospheric and coronal heating in any star.

A strong "rotation-activity" connection has been noted among the late-type stars. Going from M stars to F stars in the H-R Diagram (omitting members of binary systems), the typical stellar spin rate increases. Data from EINSTEIN show that this effect is correlated with increased x-ray emission, and hence with the strength of the corona. Among stars of the same spectral type, the rapid rotators are stronger x-ray emitters. Compelling evidence supporting the connection comes from IUE studies of short-period binaries of the RS CVn (Canum Venaticorum) type. These are cool dwarf stars that do not fill their Roche lobes and are tidally locked to their orbital periods (a few days to two weeks), so that their spin periods are much faster than usual for stars of their spectral types. These systems have remarkably strong chromospheric and transition-region emission lines, with surface brightnesses as much as one thousand times that of the undisturbed Sun in the same lines.

In the solar atmosphere, regions of enhanced magnetic field show the brightest chromospheric emission. It is popularly believed that stellar magnetic fields may be replenished by a dynamo mechanism, and the analogy has been drawn that the RS CVn systems have bright chromospheres because their rapid rotation generates magnetic flux by a stellar dynamo effect. The analogy may also apply to

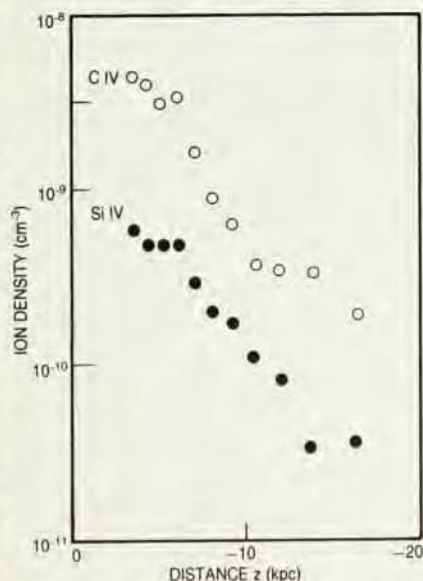
the puzzling hybrid atmospheres that exhibit both hot regions and cool, massive stellar winds. Linsky thinks these consist of two phases that may co-exist at the same level in the atmosphere. One phase parallels the magnetic loops on the Sun, which trap plasma and produce enhanced chromospheric and coronal emissions. The other phase corresponds to the open-field coronal holes and acts as the source of the stellar winds. On the Sun, coronal holes are cooler than other parts of the corona because they are cooled by expansion of the solar wind.

Supernovae, new and old

Ultraviolet astronomers are just starting to explore the supernova, a favorite toy of the astrophysicist. Young and old supernova remnants have been studied, and one very recent supernova observed by IUE has provided exciting new information.

A "young" supernova remnant is one that has not expanded very far and in which the visible material still consists entirely or mostly of the actual exploded stuff of the presupernova star. Ultraviolet observations can yield the chemical composition of the expelled layers of the star. But the only young remnant observable with IUE, the Crab Nebula, turns out to be a fairly weak source in the uv. Preliminary observations made in August 1979 by a team led by Kris Davidson (University of Minnesota) show that the abundance ratio of carbon to oxygen, a key parameter, is of order unity in the Crab (for comparison, $n(\text{C})/n(\text{O})$ is about 0.4 in the Sun), rather than the higher values implied by some models of the precursor star.

"Old" supernova remnants consist of interstellar gas swept up in the expanding shock-wave. Two well-studied objects of this type, the Cygnus Loop and the Vela X remnant, look like sparse arrangements of stringy filaments on telescopic photographs. The conspicuous filaments are thought to be thin sheets of gas seen edge-on. John Raymond (Center for Astrophysics), in studying the Cygnus Loop with IUE, has found differences in the spectra at various locations in the filaments that apparently correspond with the variation in physical conditions anticipated at various positions with respect to the shock. However, such observations can be affected by large differences in the Doppler shifts of emitting gas along the line of sight. A more unusual complication, Raymond notes, is that the intensities of the ultraviolet resonance lines are affected by the tendency of such photons to scatter out from the face of a sheet. Because one routinely selects for observation sheets that are seen edge-on the ratios of resonance-line intensities to those of forbidden lines and intercombina-



Evidence of a galactic corona, which was predicted by Lyman Spitzer Jr. in 1956, is shown in this plot of the number of carbon and silicon ions as a function of distance from the plane of the Milky Way obtained by means of the IUE. The ionic cloud extends far beyond the disk of visible material. (Courtesy of Blair Savage and Klaas de Boer.) Figure 6

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tion lines appear anomalous in the filament spectra.

Caught in the act

On 19 April 1979 an amateur astronomer in Maryland discovered a relatively bright (11th magnitude) supernova in the famous spiral galaxy M100. The star was declared a "target of opportunity" for IUE and observed repeatedly as the event developed. A recent summary of the results by Nino Panagia (Radio Astronomy Institute, Bologna) makes three main points:

- ▶ Most of the ultraviolet radiation took the form of a continuum radiated by the expanding and cooling envelope, with a temperature around 10^4 K.
- ▶ Superimposed on this bright continuum are absorption lines ascribable to gas located in the disk and corona of the Milky Way and the disk and corona of M100.
- ▶ Most interesting of all are the emission lines. They appear to originate in a rapidly expanding (~ 4000 km/s), thin, ionized circumstellar shell with a mass about one percent that of the Sun, located well outside the exploding envelope.

The gas in the shell has an anomalously high abundance ratio of nitrogen to carbon, $n(N)/n(C)$, about 10 to 30 times the value for the solar atmosphere. This observation provides insight into the situation preceding the supernova explosion. Panagia suggests that the shell consists of material expelled from the pre-supernova (perhaps a red supergiant) in the form of a massive stellar wind that has been compressed and accelerated, presumably by radiation pressure of soft x-rays from the supernova explosion.

Galactic coronas and distant objects

The IUE's ability to observe ultraviolet spectra of faint objects has enabled direct spectroscopy of individual bright blue stars in neighboring galaxies and of compact bright objects even more distant in space. The results have confirmed predictions of a galactic corona made in a now-classic paper⁵ by Spitzer.

In 1956, before the era of orbiting artificial satellites, Spitzer showed that the Galaxy must have a hot corona. He identified plausible coronal heat sources, discussed various ways that the phenomenon might be observed (recognizing ultraviolet absorption lines as the best means) and matter-of-factly observed that, "in principle, an interstellar corona could be detected and analyzed by means of spectroscopic measures from a satellite."

Last year, the necessary "measures" were at last reported. Blair Savage and Klaas de Boer (University of Wisconsin) detected the corona of the Galaxy, using as one indicator an absorp-

tion line (155 nm of C IV) specified by Spitzer in 1956. They observed hot stars in the Milky Way's satellite galaxies, the Large and Small Magellanic Clouds, and identified absorptions that, given their Doppler shifts, must arise in the Milky Way but at distances of up to 8000 parsecs from the galactic plane (figure 6). The high temperature of the corona ($\sim 100,000$ K) may well be sustained by energy from supernovae in the galactic disk, one of the heat sources originally recognized by Spitzer.

Among confirmations of the galactic corona's existence are the observation of C IV lines of the Galaxy in absorption against the continuum of the bright quasar 3C273, by a team led by Marie-Helene Ulrich (European Southern Observatory), and Panagia's detection of coronal absorptions in the ultraviolet spectra of both the M100 supernova and the nucleus of the galaxy itself. In fact, absorptions have been found that arise in the Magellanic Clouds and in M100, confirming that these galaxies also have coronas. Direct evidence for coronas in galaxies supports the idea that the "intermediate-redshift" lines found in the spectra of very distant quasars by ground-based astronomers are produced in very extended halos of intervening galaxies much closer to the Earth.

Ultraviolet observation of the most distant and exotic objects in the universe must wait for future, larger instruments in space, notably the Space Telescope. One tantalizing indication of what lies in store is the recent observation, at the limits of IUE's capability, of the binary quasar 0957 + 561. P. M. Gondhalekar (Rutherford and Appleton Laboratory) and Robert Wilson (University College London) report that measurements of the ultraviolet flux from each of the two components of 0957 + 561 reveal a magnitude ratio identical with those for the radio and optical spectral regimes. This uniformity of relative intensity over so great a range of frequencies strongly suggests that the two quasars are images of a single background object produced by a massive elliptical galaxy in the foreground acting as a gravitational "lens." (See also the story on page 17)

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