DYNAMICS, WINDS, AND STRUCTURE IN COOL STARS

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ABSTRACT

One of the many important accomplishments that astronomers have made with spectra from the IUE satellite was the recognition that dynamic phenomena and inhomogeneous structure play essential roles in the atmospheres of cool stars. While the existence of winds in cool giants and supergiants was known before its launch, IUE’s echelle spectra of ultraviolet resonance lines provided the observational material with which astronomers could measure the mass-loss rates, physical properties of the winds, and their temporal variability across the H-R Diagram. The discovery of redshifts in emission lines formed between temperatures of $3 \times 10^4$ K and $1 \times 10^5$ K showed that downflows and circulation patterns are also essential elements in the inhomogeneous structure of cool star atmospheres. Finally, the monitoring of active stars over at least a rotation period has identified analogs of solar plages and through Doppler imaging has identified where these active regions lie in the stellar chromosphere.

Key words: Late-type stars; Chromospheres; Transition regions; Stellar winds; Ultraviolet spectra; International Ultraviolet Explorer; IUE

1. ENTERING THE IUE ERA

Now that the 18 1/2 year-long observational phase of the IUE mission is complete and essentially all of the data reside in a modern archive beautifully reprocessed, it is time to summarize what IUE has accomplished and what unanswered questions should be addressed with HST, FUSE, and future missions that will use UV spectroscopy to reveal the essential physical processes underway in the atmospheres and winds of late-type stars. With your indulgence, I would like to take us back to the early morning hours of 9 February 1978 when a few of us on the Science Commissioning Team were waiting for the satellite computer to stop crashing and for IUE to acquire Capella and obtain the first high resolution spectrum of a late-type star. During the 24-hour wait for these data, and with nothing else to do, I remember thinking about what the major discoveries concerning late-type stars would be.

Even before IUE had detected its first ultraviolet photon from a celestial source, the few observations of ultraviolet and optical emission lines from a limited number of the brighter stars had already provided intriguing glimpses of the outer atmosphere layers in late-type stars. Extensive observations of the Sun had already provided some insight into layers and structures in the outer atmosphere of a cool star (e.g., chromospheres, transition regions, coronae, magnetic loops, plages, spots) and phenomena (e.g., nonradiative heating, wind acceleration, flares, nonthermal particles, radio emission, magnetic cycles) that many of us expected to be archetypes for structures and phenomena in other late-type stars. Would the Sun turn out to be a role model for all stars with convective energy transport in their photospheres, or would solar-like structures and phenomena appear only in dwarf stars, in slowly rotating middle-aged stars, or in G-type stars? We knew that IUE would provide the answers.

While waiting for IUE to finally provide a UV spectrum of Capella, I considered the information provided by the limited set of observations then available for late-type stars. The largest set of data consisted of integrated line fluxes and profiles of the Ca II H and K lines that are observable from the ground. These data, obtained largely by Olin Wilson and colleagues beginning in the 1950s, are summarized by Linsky & Avrett (1970), Wilson (1978), and Linsky (1980). These data showed that chromospheres, as indicated by the Ca II emission, are present in essentially all convective stars from spectral type F0 to the late M stars. Why the chromospheres are heated to temperatures above that expected for radiative equilibrium was not clear, but various authors had proposed acoustic and magnetic waves for the nonradiative heating process. Rather simple semi-empirical chromospheric models had been computed to match the observed Ca II emission (e.g., Kelch et al. 1979), but these were one-component homogeneous models with neither an energy equation nor magnetic fields included. The wide range of Ca II surface fluxes observed for stars at the same location in the Hertzsprung-Russell Diagram demonstrated that something other than just the stellar effective temperature and gravity must be controlling the heating process; magnetic fields were the obvious candidate, but no detailed models had then been computed. The puzzling increase in the width of the Ca II lines with absolute visual magnitude, the so-called Wilson-Bappu effect, had led many theoreticians to speculate on what it might mean, but the most plausible explanation, in terms of the increase in column density at the temperature minimum with decreasing gravity, had not yet been published. In fact, Tom Ayres was busy writing the seminal paper that morning on the control room floor (Ayers 1979). Finally, the search was on to find stellar cycles using the Ca II flux. At this time, the variability in flux also hinted at rotational modulation by stellar analogs of solar plages (e.g., Wilson 1978); the full flowering of the Mt. Wilson HK program would come later.
There was also some information about the presence of hotter plasma in the outer atmospheres of late-type stars from observations obtained with the Copernicus satellite, rockets, the balloon-born UV spectrometer (BUSS), and ground-based observations in the He I 10830Å lines. Although severely limited in sensitivity, S/N, and spectral coverage, these few snapshots provided some intriguing clues. For example, spectra of the Mg II h and k lines (2803Å and 2796Å), which are analogs of the Ca II lines, were obtained with both the Copernicus satellite (e.g., Weiler & Oegerle 1978) and the BUSS instrument (Kondo et al. 1972). These data showed that the Wilson-Bappu effect also applies to the Mg II lines. The better exposed spectra of luminous stars with broad profiles (e.g., α Ori, α Tau, and α Tuc) are asymmetric, presumably due to winds. Higher quality spectra with IUE and GHRS would later separate wind absorption from interstellar and overlying circumstellar absorption lines, as we will illustrate below. Copernicus spectra had already shown both strong Lyman-α emission in a number of stars and weak, but real, emission in the S III 1206Å and O VI 1032Å lines from Procyon (Evans et al. 1973) and Capella (Dupree 1975). A beautiful UV rocket spectrum of Capella (Vitz et al. 1976) had shown emission lines of O I, C II, Si IV, and C IV, leading to the first model of the transition region of a star other than the Sun (Haisch & Linsky 1976).

What were missing in the pre-IUE era were sensitive observations of many emission lines from a wide variety of stars, line profile information, had paid sufficient attention and theoretical interpretation. The IUE data set is split into its low-resolution and high-resolution portions to indicate whether line fluxes or line profiles were needed to discover the phenomenon.

IUE provided many of these discoveries, but at least one additional discovery (that of broad components in transition line profiles) could have been identified in the IUE data set if the observers had paid sufficient attention and trusted the IUE instrumental line profile. This nondiscovery is marked in the table as CH for “could have”. As previously mentioned, optical ground-based observations in the Ca II and Hα lines had identified the cooler plasma at the base of stellar chromospheres, so the designation “D” in the first four entries of the table refer to plasma hotter than that observable with the Ca II and Hα lines.

The discovery of new phenomena provides only the beginning of understanding. Entries in the table marked I and MI refer to data sets that are improvements or major improvements over the discovery data sets. It is with data sets marked I and MI that one can begin to understand the physical processes responsible for the phenomena and thus build sophisticated physical models to compare with the high-quality data. This is how IUE has made its major contributions, and where the GHRS and STIS instruments will improve on what IUE has done. Since there is insufficient time or space to describe all of these phenomena, I will concentrate on those involving dynamics that have changed our understanding of the atmospheres of cool stars.

3. REDSHIFTS AND PLASMA FLOWS

In the first detailed analysis of IUE echelle spectra of the Capella system, Ayres and Linsky (1980) found that the emission lines of transition-region ions (e.g., C II, Si IV, and C IV) are redshifted relative to the low-temperature chromospheric emission lines. They were surprised by this discovery because earlier Copernicus observations had appeared to show that these lines are blueshifted and that the blueshifts increase with line-formation temperature as expected for an accelerating stellar wind. Their discovery was followed up by careful observations of Capella at conjunction (when both stars have the same radial velocity) and of other late-type dwarfs and giants (e.g., Ayres 1984; Ayres et al. 1983, 1988) which provided the following results:

- All transition region lines, including the optically thin interstellar Si III 1892Å and C III 1090Å emission lines, are redshifted relative to the low-temperature chromospheric lines in all of the stars studied. Since the interstellar lines show Doppler shifts roughly similar to those of the permitted lines, which could be optically thick, the observed redshifts must indicate true downflows, rather than a radiative transfer effect produced by an accelerating outflow.

- The downflow velocities increase with the temperature of line formation between $3 \times 10^4$ and $1 \times 10^5$ K, although the data show considerable scatter.

- There is a tendency for lower-gravity stars (e.g., 9 Dra and Capella) to show larger redshifts ($\geq 20$ km s$^{-1}$) at $10^5$ K (Brown et al. 1984) than dwarf stars (e.g., α Cen A, α Cen B, ε Eri) which show $\approx 10$ km s$^{-1}$ redshifts.

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Table 1. Role of IUE in the discovery of new phenomena in cool stars.

<table>
<thead>
<tr>
<th>Phenomenon/critical observations</th>
<th>Pre-IUE</th>
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D = Discovery; I = improvement; MI = major improvement; CH = could have.

GHRS spectra confirm the main conclusions obtained from the IUE data, but with much lower scatter in the trends of velocity with line-formation temperature. In the most complete data set, Wood et al. (1997) find that the redshifts decrease about the trend line for Procyon, with little scatter until at least log T = 5.3, at which temperature the N V and O V I lines are formed and the redshift is 10 km s⁻¹. The Sun, α Cen A, and α Cen B appear to differ from the F3 IV-V star Procyon as their redshifts decrease at temperatures above 1 × 10⁵ K.

What could be the cause of the redshifts, and what implications do they have for our picture of stellar atmospheres? High spatial-resolution solar observations provide an important clue. Downflows have now been studied with SKYLAB, OSO-8, SMM, the HRTS rocket, and EUV spectrometers (see Brekke 1993 and Achour et al. 1995 for references). While the redshifts are seen in spatially averaged quiet Sun spectra, they are much stronger in active regions where magnetic fields are strongest and the emission lines brightest. For example, Achour et al. (1995) found that in quiet regions the redshift of the C IV 1548Å line formed at 1 × 10⁵ K is 6.2 km s⁻¹, compared to 13.0 km s⁻¹ in active regions. Thus the spatial averaging that occurs when we observe a star as a point source should result in a net redshift. Observations of the solar EUV spectrum with the CDS and SUMER instruments on SOHO (Bryndilson et al., 1998) now show that the redshifts are a property of the transition region up to temperatures of at least 650,000 K where the O VI and Ne VIII lines are formed. Stellar observations of the O VI lines by the FUSE satellite will determine whether this trend is present in some or all cool stars.

The spatial correlation of redshift with magnetic field leads naturally to models in which the gas flows are directed downward along magnetic flux tubes where the heating is concentrated. For example, the models of Reale et al. (1996), which are computed with a 2-D hydrodynamical code, show that density perturbations in regions of strong density and temperature stratification, such as the solar transition region, cool radiatively to become condensations that flow downward by gravity. These models show typical downflow velocities ≥ 5 km s⁻¹, which are consistent with the observed solar values at 10⁵ K. Achour et al. (1995) summarized other proposed models which include downflows in magnetic flux tubes induced by nanoflares, infall of spicules after they reach the top of their trajectories, and circulation patterns along flux tubes for cases in which either the downflowing legs have higher densities than the upflowing legs (Ayers et al. 1983) or the heating is predominantly in one leg (McKee and Crider 1987). These IUE, GHRS, and solar observations, together with all of the proposed explanations, highlight the importance of including magnetic fields, flows, and inhomogeneities in realistic models of the atmospheres of cool stars. Homogeneous, static models are clearly unrealistic.
4. PROPERTIES OF COOL-STAR WINDS

IUE echelle spectra of the optically thick Mg II and k resonance lines provided a powerful new tool for both identifying the presence of winds in late-type stars and measuring their properties, including the outflow velocity as a function of radial position often called the “velocity law” \( v(R) \), the terminal velocity \( v_\infty \), and the mass-loss rate \( \dot{M} \). As listed in Table 1, the latter two quantities had been estimated prior to IUE for some of the brighter and more luminous cool stars using blue-shifted circumstellar absorption features in the Ca II, Na I, and K I resonance lines present in ground-based spectra. These earlier analyses yielded only rough measurements of the wind properties, because the lines used were often from trace species whose ionization equilibria were uncertain. Moreover, these lines usually were not optically thick enough to sample the wind at the terminal velocity.

IUE echelle spectra of the Mg II and k lines provided a major improvement over the earlier work as these Mg II lines sampled the wind further away from the star, where Mg II is often the dominant stage of ionization, so that uncertainties in the ionization equilibrium were less important. Although a few Copernicus and BUSS spectra of the Mg II lines were available prior to IUE to whet our appetite, IUE has provided the vast majority of high-resolution spectra that provide information on cool-star winds. IUE echelle spectra of single cool stars include other lines that show either asymmetries or blue-shifted absorption features, such as the Lyman-\( \alpha \), the O I 1302, 1304, 1306 Å triplet, and the Fe II resonance lines near 2600 Å; however, these lines are more difficult to interpret than the Mg II lines.

A major problem that affects the analysis of all of these lines is the identification of and subsequent correction for interstellar absorption lines, which typically occur within 25 km s\(^{-1}\) of the rest wavelength and obliterate most of the center of the Lyman-\( \alpha \) line. Since the echelle resolution (\( \approx 30 \) km s\(^{-1}\)) of IUE cannot resolve the narrow interstellar absorption lines, GHRSS echelle spectra with a resolution of 3.5 km s\(^{-1}\) are needed to cleanly separate the stellar emission line and wind absorption features from the interstellar absorption. Figure 1 makes it clear that IUE echelle spectra can show that interstellar absorption is present but not resolve its structure. Also, IUE spectra can provide a good estimate of typical flow speeds of the Mg II ions in the wind, but these spectra cannot determine accurately the shape of the wind absorption feature needed to determine the maximum wind speed and turbulent velocities in the wind. Despite these problems, IUE spectra have played key roles in our understanding of the winds of cool stars.

There are a number of important reviews of the observations of cool star winds (e.g., Dupree 1986; Dupree and Reimers 1987) and the theory of wind acceleration in these stars (e.g., Holzer 1987; Judge 1992). What follows is my assessment of the major accomplishments of IUE concerning the winds of cool stars:

4.1. Which Types of Stars Have Winds?

IUE detected no clear evidence for outflowing gas in any dwarf star of spectral type F, G, K, or M; no detection was expected, given the low mass loss rate \( \dot{M} \approx 2 \times 10^{-14} \) M\(_{\odot} \) yr\(^{-1}\) and 10\(^6\) K temperature of the solar wind. The one possible exception is the V471 Tau binary system for which Mullan et al. (1989) have presented evidence for blue-shifted absorption features in chromospheric lines of the K2 V star seen in projection against the continuum of the hot white dwarf companion. Their tentative detection of a wind from the K dwarf star with a mass-loss rate \( \dot{M} \geq 10^{-11} \) M\(_{\odot} \) yr\(^{-1}\) requires confirmation. A new approach for detecting winds in solar-type stars uses the higher spectral resolution of the GHRSS to discover “hydrogen walls” around the stars produced by the interaction of the interstellar medium and the stellar wind (Wood & Linsky 1998).

For the more luminous cool stars, the signatures of mass loss become increasingly prominent toward the upper right half of the HR Diagram. In an early survey of the Mg II emission lines, Stencil & Mullan (1980) found that the giants later than about spectral type K2 III and the G, K and M supergiants show asymmetric Mg II emission lines, with the blue emission peak depressed with respect to the red emission peak as the lines are formed in an accelerating outflow. It is not yet clear whether the onset of observable line asymmetries indicates the true onset of cool winds, or whether cool winds exist in warmer and less luminous stars, but in such cases the Mg II optical depth in these winds is too small to detect.

Other unanswered questions include: whether the transition from hot winds in solar-type stars to cool winds in the more luminous stars is sharp with changing stellar parameters (presumably due to an instability) or gradual, whether intermediate-temperature winds exist, and whether both cool and hot winds can coexist on the same star but in different (presumably magnetic) structures.

4.2. What are the Speeds of Cool Star Winds?

Both the velocity of maximum blueshift and the minimum intensity of the Mg II absorption features have been used to estimate the asymptotic flow speed of the wind, \( v_\infty \). However, both measures may give lower bounds to \( v_\infty \) as turbulent motions can extend the maximum blueshift of the absorption (see Figure 1). Also, the flow may be faster far away from the star where the Mg II lines are optically thin perhaps due to ionization. A further complication is that interstellar absorption lines can occur near the wind velocity of a cool supergiant like \( \alpha \) Ori or appear to be a low velocity component in the wind of a warmer star (Drake et al. 1984). Dupree & Reimers (1987) have summarized estimates of \( v_\infty \) using the minimum-intensity point criterion. They cite velocities up to 180 km s\(^{-1}\), with the velocities of the hybrid stars (see below) significantly larger than those of the more luminous (and lower gravity) supergiants. Unlike the OB stars, the winds of all of the luminous cool stars studied to date show flow speeds that are less than the escape speed from the photosphere. This result provides an important constraint on acceptable mechanisms for accelerating winds in these stars (cf. Holzer 1987).

There is evidence for nonperiodic variability of hybrid star winds by stochastic processes (Brown et al. 1996), and evidence for periodic changes in the wind of the M supergiant \( \alpha \) Ori likely driven by pulsations (Dupree et al. 1987).
4.3. What are the Temperatures of Cool Star Winds?

The presence of outflows as seen in the Mg II lines implies a wind temperature in the range of 5,000 to 10,000 K, unless Mg$^+$ is a minority species. Dupree & Reimers (1987) summarize various studies that indicate wind temperatures in this range. However, the case for low-temperature winds is more complicated. Hartmann et al. (1980) found that some bright K giants (like α TrA) and G supergiants (like α Aqr) show blue-shifted Mg II absorption and emission lines from ions present at 10$^5$ K. This new class of “hybrid-chromosphere” or more commonly called “hybrid” stars makes it clear that there is no simple division of the cool half of the HR Diagram into stars with only high-temperature plasma and hot winds, on the one hand, and stars with only low-temperature plasma and cool winds, on the other.

Do the hybrid stars show warm 10$^5$ K winds intermediate between the solar-like dwarfs and the cool supergiants? This idea has been proposed, and it is consistent with the predictions of Alfvén wave-driven wind models (e.g., Hartmann et al. 1981); however, there are no IUE observations to support it. In particular, Brown et al. (1986) find that the optically thin interstellar lines of C II, C III], and Si III] in the spectrum of α TrA show no blueshifts. We are therefore left with two possibilities – either the high-temperature plasma is stationary, perhaps confined in closed-field regions, or the wind reaches temperatures of 10$^5$ K only far from the star where the transition-region lines are optically thin. Observations with HST and FUSE are needed to answer this question. One new observation with the GHRS instrument on HST is the detection of a wind absorption feature in the Si III 1206Å line of α TrA, which Harper et al. (1998) interpret as outflowing material with a temperature of about 20,000 K. At this temperature magnesium is predominately Mg$^{++}$, and the inferred mass-loss rate, $\dot{M} \approx 2.0 \times 10^{-9} M_\odot$ yr$^{-1}$, is a factor of 5 times larger than if one assumed that all of the magnesium is Mg$^+$. 

4.4. What are Mass Loss Rates?

A major goal of the study of cool stars is to measure mass loss rates, because mass-loss can influence stellar evolution and because the input of chemically modified material into the interstellar medium from which new stars are formed is a critical element of galactic evolution. IUE has played an important role in this topic, but there are critical uncertainties in the process of inferring mass-loss rates from line profiles. As summarized by Linsky et al. (1998), these uncertainties are in the assumed geometry, velocity law, magnetic fields, ionization, radiative transfer, turbulence in the wind, and the influence of a binary companion.
Perhaps the most accurate values for the mass loss are obtained from eclipsing binary systems, in particular the ζ Aur systems, which consist of K supergiant and a B-type main sequence star. The latter provides the bright UV continuum against which many lines of Fe II, Si II, and other ions in the K star’s wind appear either as blue-shifted absorption or as P Cygni-type profiles with both absorption and emission components. The ability to analyze many lines formed in the wind with different optical depths and to sample different lines of sight at different orbital phases leads to more reliable mass-loss rate estimates. The work of the Hamburg School of Reimers and coworkers indicates mass-loss rates in the range of 10^{-8} to 10^{-5} M☉ yr^{-1} for the ζ Aur and related binary systems (see Table II in Dupree & Reimers (1987), and Reimers (1987) has proposed a scaling law for the mass loss,

$$M = 4 \times 10^{-13} \frac{n(L/L_\odot)}{(g/\Omega)(R/R_\odot)} \frac{M_\odot}{yr}$$

with 1/3 < n < 3.

Analysis of these systems is continuing with multiphase observations by the GHRs and STIS instruments on HST. A critical question is whether variations in wind speeds, ionization, and column densities imply corresponding changes in the mass-loss rates. In their recent review of this question, Linsky et al. (1998) conclude that for the stars studied in detail (the Sun, α TrA, λ Vel, and ζ Aur), variations in the mass-loss rates with time appear to be only a factor of 2 or less.

5. EVIDENCE FOR ATMOSPHERIC STRUCTURES

Theoretical models of the outer atmosphere layers of cool stars typically assume that the physical properties (e.g., temperature, density, pressure, turbulent speed, outflow speed, ionization) can be specified as unique functions of height (or optical depth) in a plane-parallel or spherically-symmetric geometry. Images of the solar atmosphere in UV emission lines, Hα, and x-rays, however, demonstrate that the solar atmosphere is highly inhomogeneous with structures defined by the magnetic field geometry. Spatially-resolved images of cool stars with many resolution elements across the surface are not yet feasible, although the first HST/FOS images of α Ori with a few resolution elements across the surface have been obtained by Gilliland & Dupree (1996). Indirect imaging techniques are now providing the first, albeit fuzzy, images that show bright active regions on some stars. For reviews of this topic see Linsky (1990), Pagano et al. (1992), Walter (1996), and other papers in the proceedings of IAU Symposium No. 176, Stellar Surface Structure.

Photometric monitoring of active stars in the UBV filter bands is often used to locate dark star spots on stellar surfaces. Hall (1996) has reviewed this topic thoughtfully with emphasis on the unanswered questions. IUE was the ideal instrument for monitoring the emission line fluxes of active stars over a rotation period to locate bright plage regions in stellar chromospheres. Rodonó et al. (1987) pioneered this rotational modelling technique in their study of the single-lined spectroscopic binary II Peg, which showed a very bright plage during their October 1981 monitoring campaign. When the plage was visible, the integrated fluxes of the Mg II lines were a factor of 2 larger and the integrated fluxes of the transition-region lines were a factor of 5 higher than when the plage was not visible. The rotational modulation technique has been successfully applied to other RS CVn systems; the technique provides accurate estimates of plage longitudes, rough estimates of plage latitudes when the inclination of the rotation pole is known, but no information on the plage sizes.

Vogt and Penrod (1983) pioneered the Doppler imaging technique, which can determine the location and sizes of dark star spots from the changing wavelength of a bright feature superimposed upon a rotationally-broadened line profile beginning when the dark star spot rotates into view (maximum blueshift) until it rotates off the receding limb (maximum redshift). Walter et al. (1987) and Neff et al. (1989) have applied this technique, which is often called “spectral imaging,” to the analysis of bright areas in the stellar chromosphere that produce narrow emission features superimposed upon the Mg II h and k lines. This technique can determine the plage longitudes from the times that the plage emission feature crosses line center, the plage latitudes from the duration of visibility (provided the inclination of the stellar rotation axis is known), and the extension of the plage in longitude (and thus its approximate size) from the width of the emission feature. In this way they were able to determine the stellar coordinates and sizes of 2 plages on AR Lac in the February 1983 observing campaign and 3 plages in September 1985. These and other campaigns to monitor AR Lac and other RS CVn systems (e.g., Pagano et al. 1992) have led to the following results:

- Plages have now been observed near the equator and at high latitude (near ±50°) on the K0 IV star in the AR Lac system.
- Plage sizes have been detected as large as 9% of the visible surface and as small as ≤ 1% of the visible surface.
- Plages migrate across the stellar surface at a rather slow rate (10–20 degrees per year), implying slow differential rotation in RS CVn systems compared to the Sun.
- In many cases the maximum radial velocities at the beginning and end of visibility exceed the equatorial rotation velocity of the star. This implies that the plages extend to ≥ 0.5 stellar radii above the star if they rigidly rotate and flows are not important.
- From the plage sizes and fluxes one can infer the mean plage surface fluxes. These are typically 4 times that of the quiet surface in the Mg II lines and 4–13 times that of the quiet surface in the transition-region lines. As a result, the total radiative power emitted by the plage chromosphere and transition region must be balanced by heating rates at the maximum levels seen in the most rapidly-rotating active stars (Vilhu 1987; Linsky 1991). This result is consistent with the idea that plages are regions of strong magnetic fields and saturated heating rates.

The GHRs and STIS instruments on HST can extend the spectral imaging technique to study plages in the transition-region lines and to measure the plage sizes more accurately as a result of the higher S/N, sensitivity, and spectral resolution of the HST instruments. The results of one short campaign to study HR 1099 with the GHRs has been published (Dempsey et al. 1996), but it is very difficult to schedule an HST monitoring campaign.
to include a full rotation period as we were able to do successfully with IUE.

6. CONCLUSIONS

Nearly 20 years ago at the start of the IUE era, we had only vague ideas concerning what this new satellite would tell us about late-type stars. Now, after more than 100,000 ultraviolet spectra and many publications, of which I have cited only a very small sample, I believe that IUE has gone far in revealing the complexity of the atmospheres of real stars that realistic theoretical and semiempirical models must now include. In particular, we now have clear evidence for dynamic phenomena (winds and downflows) and inhomogeneous atmospheric structure. I urge that future analyses and models include these important facts that IUE has kindly provided for us.

ACKNOWLEDGEMENTS

I am grateful for the support NASA through many grants to the University of Colorado. I also thank my many colleagues, including Tom Ayres, Alex Brown, John Butler, Gerry Doyle, Steve Drake, Bernhard Haisch, Graham Harper, Jim Neff, Marcello Rodonò, Steve Saar, Ted Simon, Fred Walter, Brian Wood, and the late Brendan Byrne with whom I have had the pleasure of making many discoveries when analyzing IUE data.

Brendan, we miss your lively discussions and insightful comments.

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