Key problems in cool-star astrophysics

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Abstract

Selected key problems in cool-star astrophysics are reviewed, with emphasis on the importance of new ultraviolet missions to tackle the unresolved issues.

UV spectral signatures are an essential probe of critical physical processes related to the production and transport of magnetic energy in astrophysical plasmas ranging, for example, from stellar coronae, to the magnetospheres of magnetars, and the accretion disks of protostars and Active Galactic Nuclei. From an historical point of view, our comprehension of such processes has been closely tied to our understanding of solar/stellar magnetic activity, which has its origins in a poorly understood convection-powered internal magnetic dynamo. The evolution of the Sun's dynamo, and associated magnetic activity, affected the development of planetary atmospheres in the early solar system, and the conditions in which life arose on the primitive Earth. The gradual fading of magnetic activity as the Sun grows old likewise will have profound consequences for the future heliospheric environment. Beyond the Sun, the magnetic activity of stars can influence their close-in companions, and vice versa.

Cool star outer atmospheres thus represent an important laboratory in which magnetic activity phenomena can be studied under a wide variety of conditions, allowing us to gain insight into the fundamental processes involved. The UV range is especially useful for such studies because it contains powerful diagnostics extending from warm ($\sim 10^4$ K) chromospheres

out to hot (1–10 MK) coronae, and very high-resolution spectroscopy in the UV has been demonstrated by the GHRS and STIS instruments on *HST* but has not yet been demonstrated in the higher energy EUV and X-ray bands. A recent example is the use of the hydrogen Lyα resonance line—at 110 000 resolution with *HST* STIS—to study, for the first time, coronal winds from cool stars through their interaction with the interstellar gas. These winds cannot be detected from the ground, for lack of suitable diagnostics; or in the X-rays, because the outflowing gas is too thin.

A 2m class UV space telescope with high resolution spectroscopy and monitoring capabilities would enable important new discoveries in cool-star astronomy among the stars of the solar neighborhood out to about 150 pc. A larger aperture facility (4–6m) would reach beyond the 150 pc horizon to fainter objects including young brown dwarfs and pre-main sequence stars in star-forming regions like Orion, and magnetic active stars in distant clusters beyond the Pleiades and α Persei. This would be essential, as well, to characterize the outer atmospheres of stars with planets, that will be discovered by future space missions like *COROT*, *Kepler*, and *Darwin*.

1 Introduction

Magnetic activity signatures, analogous to well-known solar phenomena, are widely observed in cool stars. Dark cool spots in the stellar photosphere produce modulations of optical light curves as the star rotates, and the migration of Doppler shifted features through the line profiles. Flares, coronal mass ejections (CME's), and stellar winds (of luminous cool stars) are commonly observed. Magnetic activity also is responsible for prominent emission-line spectra in the ultraviolet and far-ultraviolet (UV/FUV) regions, and for the entire stellar X-ray and radio emission.

In RS CVn-type binary systems, dMe stars, and young rapidly rotating dwarfs, magnetic activity is of paramount interest because of its extreme characteristics: in such stars more than 50% of the stellar photosphere can be spotted, chromospheric and transition region (TR) fluxes are so high that they have topped out at a saturation limit, and the X-ray luminosity can even reach a remarkable 10^{-3} of the stellar bolometric luminosity, ten thousand times larger than the equivalent solar ratio.

Thanks to long-term systematic monitoring programs of highly convective cool stars initiated in the mid sixties, notably at Crimea [Chugainov1966], Catania [Godoli1968] and Mt. Wilson [Wilson1978] and successively pursued worldwide at other Observatories (e.g., Vienna, Konkoly, Armagh, Potsdam and Fairborn), about forty years later we are now in a position to state

with confidence that many cool stars show periodic variations of their emissions from almost all atmospheric layers with characteristics similar to the

11-year solar cycle (Wilson; Bal95; Rodono95, 2000, 2002; Str97; Lanza98, 2002; Cutispoto01, 2003; Olah; Messina01; MG02, 2003; Favata). However, there are also phenomena that do not have analogues on the Sun: high-latitude [Rodonò1986] and polar spots (S90, S91), very hot (>10 MK) coronal components [Linsky2003, Audard et al.2004], etc.[1]. As for the Sun, however, the activity phenomena occurring in the different atmospheric layers of cool stars appear to be closely correlated [Catalano et al.2000, Messina et al.2002].

The Sun's contemporary magnetic activity affects the Earth's biosphere and human civilization through a variety of phenomena lumped under the heading "space weather." Furthermore, the Sun was considerably more active in its youth than today (e.g., Ribas2005), and had a correspondingly larger impact on the solar system, especially primitive planetary atmospheres and the environment in which life began on Earth. Given the importance of accurately forecasting solar-related influences—now, in the past, and in the future—it is essential to investigate how magnetic activity depends upon stellar parameters (mass, radius, rotation rate, binarity, evolutionary stage, etc.) if we ever want to develop a theory for these high-energy phenomena that has predictive power.

Hot plasma in magnetically disturbed cool-star outer atmospheres, with temperatures from 10 000 K to several millions, can be observed in a single ultraviolet spectrum, providing simultaneous information on thermal structures of a wide range of atmospheric components. As an example, Fig. 1 illustrates the spectrum of α Cen A (G2 V) obtained with *HST*/STIS in the range 1140-1670 Å with a resolution R∼114,000 (E140H). In this spectrum Pagano04 identify a total of 671 emission lines from 37 different ions, including low temperature chromospheric lines (e.g., C I, O I), TR lines (e.g., C II–IV, N IV, O III–V, Si II–IV), the coronal line Fe XII 1242 Å, a number of intersystem lines (e.g. [O IV]) that are useful for measuring electron densities, and two molecules (CO and H_2).

In what follows, we emphasize the importance of the ultraviolet for addressing unresolved issues in the study of cool stars and related objects.

2 A Brief History of UV Cool-Star Astronomy

Ultraviolet astronomy has been crucial to the study of cool stars. Although the photospheric spectral energy distribution of this type of star peaks at red wavelengths, the presence of hot plasma in chromospheres, transition regions, and coronae reveals itself most prominently through emission at the shorter ultraviolet wavelengths, where conveniently the photospheric contribution typically is faint.

A comprehensive account of the development of UV astronomy from the pioneering rocket experiments of the 1960's until the era of the prolific International Ultraviolet Explorer (*IUE*) can be found in the review by BW87. In summary, the first ultraviolet stellar spectra with sufficient resolution to detect emission lines were obtained during a rocket flight in 1965. In the nine years from 1964

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[1] Detailed descriptions and references for all the phenomena mentioned above and the associated theoretical scenarios can be found in the Proceedings of the Cambridge Workshops "Cool Stars, Stellar Systems and the Sun", published in the Astronomical Society of the Pacific Conference Series.

to 1972, NASA's Orbiting Astronomical Observatories (*OAO's*) constituted the first programme of space facilities designed specifically for ultraviolet astronomy. In particular, the final one, *OAO–C*—launched in 1972 and designated *Copernicus*—detected for the first time FUV emission lines in two UV-bright cool stars, namely Procyon (α CMi) and Capella (α Aur). In parallel, the first European satellite carrying several UV experiments was *TD–1*, launched in 1972.

The technological efforts and the scientific needs of the UV astronomical community crystallized in the joint NASA, ESA and British SERC *IUE* project, launched in January 1978 and finally terminated in September 1996, after an extraordinarily long and productive mission. The broad *IUE* coverage (1100–3200 Å), high spectral resolution (up to R = $\lambda/\Delta\lambda$ =10 000 in its echelle modes), and higher sensitivity than previous UV missions provided numerous key discoveries in many different areas of cool-star science, from the atmospheres of T Tauri stars [Imhoff & Appenzeller1987], accretion processes in pre-main sequence stars, winds in Herbig Ae/Be stars, chromospheres and transition regions in all kinds of late-type stars [Jordan & Linsky1987], and Doppler imaging of the components (and atmospheres) of active binary systems, and stellar winds [Dupree & Reimers1987]. Detailed summaries of the achievements in each of these fields at the end of the IUE mission can be found in the Proceedings of the Conference "Ultraviolet Astrophysics beyond the IUE Final Archive" [Wamsteker & González-Riestra1998].

Following *IUE*, three missions have made further and substantial contributions to UV astronomy of cool stars, namely the Hubble Space Telescope (*HST*), the Extreme Ultraviolet Explorer (*EUVE*) and the Far Ultraviolet Spectroscopic Explorer (*FUSE*).

Three UV instruments on board *HST* have made pivotal discoveries in cool-star science. The Goddard High Resolution Spectrograph (GHRS) covered the interval 1150–3200 Å, with resolutions between 2 000 and 80 000. The companion Faint Object Spectrograph (FOS) covered the broad region from Lyα into the visible, although at relatively low resolution and with significant scattered light below 1900 Å. Nevertheless, FOS filled an important gap during the period when GHRS was not able to use its own low-resolution mode owing to an electrical failure [Ayres et al.1996]. The second-generation Space Telescope Imaging Spectrograph (STIS) covered the wavelength range 1150–10 000 Å, with spectral resolving powers between 26 and 200 000. GHRS and FOS were in operation from 1990 until 1997; STIS carried on from then until a power supply failure in August 2004. The *HST* UV instruments covered the same range as *IUE*, but the much larger telescope aperture, higher spectral resolution in some of the observing modes, more sensitive digital cameras, and the ability to achieve high spatial resolution (in STIS long-slit modes) permitted observations of cool stars many magnitudes fainter than the targets accessible in the pre-*HST* era. A good example of the science added by the *HST* instruments is a survey of FUV coronal forbidden lines carried out by Ayres03a in a sample of F–M dwarfs, giants and supergiants, detecting faint lines from highly ionized species such as Fe XXI 1354 Å, formed at 10^7 K. The UV coronal forbidden lines are diagnostically unique because they can be recorded at high spectral resolution much more easily than their permitted counterparts in the X-ray region (where the current best resolution is only about 1,500). Contributions in all other UV fields, already opened by *IUE* were also remarkable and valuable.

EUVE was launched in 1992 and operated until January 2001. It covered the extreme ultraviolet wavelengths from 60 Å up to the Lyman continuum (LyC) edge at 912 Å (although in practice few stars were observable longward of ∼400 Å owing to interstellar extinction). Of the 734 sources cataloged in *EUVE*'s all-sky survey, 55% were identified as late-type stars. *EUVE*'s ability to resolve spectral lines from a variety of high ionization stages was of tremendous value for modeling the temperature structure of stellar coronae, and many such studies of stars of different activity levels were carried out. *EUVE* also enabled for the first time the study of stellar coronal abundances and chemical fractionation phenomena such as the so-called FIP-effect (elements with First Ionization Potentials $<$ 10 eV are overabundant in the solar corona compared with high-FIP counterparts, e.g. Osten2003). Equally important, the long continuous stares of days to weeks, motivated by operational considerations, made *EUVE* an ideal platform to study coronal variability, especially flare activity. An account of the achievements of *EUVE* can be found in BDV00.

FUSE, launched in 1999, records the 912–1187 Å spectrum with four separate telescope/spectrograph channels (further subdivided by redundant detector segments). The *FUSE* range includes the strong Li-like O VI 1031,37 Å resonance doublet, formed at transition region (TR) temperatures around 300 000 K, as well as the very strong C III 977 Å resonance line, formed near 60 000 K. Like STIS, *FUSE* provides a link to coronal dynamics through the [Fe XVIII] 974 Å and [Fe XIX] 1118 Å forbidden lines (cf. Redfield03). Molecular hydrogen absorption, and fluorescence of H_2 by H Lyα, add further diagnostics for determining plasma densities, temperatures, and structural constraints in, for example, circumstellar envelopes of Herbig Ae/Be and T Tauri stars. Two important papers are the surveys of cool dwarfs [Redfield et al.2002] and giants [Dupree et al.2005]. H04 and A05 have reviewed recent *FUSE* results on cool stars.

3 Open Issues

In the remainder of the paper we focus in the remainder of the paper on a few selected open issues in cool-star physics that can be addressed by new observations in the ultraviolet spectral range. These issues are, in our opinion, important topics in stellar physics and key ingredients for progress in the fields of “space weather,” “extrasolar planets,” and “life beyond Earth.”

- Stellar dynamos and the transport of magnetic energy in plasmas;
- Magnetic activity of stars hosting planets;
- Astrospheres and solar-like stellar winds;

- Activity in young galactic clusters and star-forming regions.

3.1 Stellar dynamos and the transport of magnetic energy in plasmas

In stars of spectral type early F and later, the coupling between differential rotation and turbulent convection in their subphotospheric layers generates strong magnetic flux ropes, by a mechanism known as "dynamo action", first investigated for the stellar case by BPS80a,b,c). The tubes buoyantly rise through the convection zone, penetrate the stellar surface, become braided and twisted by surface velocity fields, and ultimately reconnect releasing their magnetic free energy to power the nonclassical outer atmospheric activity that is a focus of much solar/stellar research today. Existing models of the dynamo are able to reproduce gross features of the 11-year sunspot cycle, and the 22-year period of the Sun's global magnetic field reversals. However, contemporary dynamo models cannot forecast the details of solar activity on short time scales of months to years (cf. review by Paterno).

One of the challenges of dynamo theory today is to explain the characteristic periods of the quasi-cyclic activity oscillations of stars and, in particular, the problem of the large observed ratio (>100) of cycle times and correlation times of the turbulent eddies. While in an evolutionary scenario the actual picture of the dynamo action ranges from an α^2 in fully convective stars to $\alpha\Omega$ dynamo regime in solar-type stars, it has been recognized that a necessary ingredient to explain the observational features of magnetic activity in the Sun is the inclusion of the meridional circulation together with a small eddy diffusivity [Bonanno et al.2005]. In this case the magnetic Reynolds number reaches 100-1000 and the dynamo action correctly reproduces all the observations (cycle times, butterfly diagram, sign of the current helicity, ratio of toroidal/poloidal field strengths) with a differential rotation profile as provided from helioseismology. Another key issue in understanding the "solar-stellar connection" in terms of dynamo theory, and more generally the evolution between α^2 regime and the $\alpha\Omega$ one, is the so-called "flip-flop" mechanism observed in some RS CVn's and single young dwarfs (see also Sect. 3.1.1).

Only in recent decades have we begun to appreciate the effects of short-term solar variability on the Earth's environment and human civilization. Major solar flares and CME's can cause electronic failures in commercial and scientific satellites, disrupt long distance radio communications, and induce ground currents than can overload electricity transmission grids. Moreover, there is growing evidence that solar activity can, to a certain extent, influence the Earth's climate.

For example, historical records of sunspot counts show that solar activity decreased for more than 50 years during the 17th century when Northern Europe was experiencing the "Little Ice Age." On the other hand, a sustained increase of activity, in a modern version of the "Grand Maximum" that occurred during the 12th century, might cause climate warming and the increase in space storms and ultraviolet radiation, which is harmful to life, particularly if protective ozone layers continue to diminish as a consequence of anthropomorphic emissions.

Butler and PBB have found quantitative evidence that much of the warming of the past century can be accounted for by the direct and indirect effects of solar activity. However, at the moment we cannot forecast long and short-term solar magnetic variability because we do not have a comprehensive understanding of their root causes: the dynamo mechanism and the physical processes that shape plasma structure and control dynamics in the solar outer atmosphere. One way to progress in this area is to step back from the Sun, and instead evaluate how magnetic activity phenomena depend on fundamental stellar parameters: mass, rotation rate, chemical composition, binarity, and so forth. The diverse stellar examples of activity might reveal insights into the underlying physical processes that observations of the singular example of our Sun cannot, no matter how detailed.

In what follows, potential new observational constraints on the stellar dynamo and the mechanisms of coronal heating are discussed.

3.1.1 Determining the locations and migration patterns of active structures

Observational constraints on stellar dynamos can be obtained by imaging the surface patterns of magnetic activity in large samples of stars. We already know that on other stars the mean locations of magnetic active regions and their migration paths can be different from those observed on the Sun [Walter2003]. In some cases, highly active stars show polar spots, migration of active regions toward the poles, preferred active longitudes, a "flip-flop" effect, i.e. sequential activation of a pair of active longitudes (see, e.g., Rodono, BT98).

Much of the existing work on surface patterns of stellar magnetic fields has involved optical observations of large dark starspots, the sites of concentrated strong (kilogauss) magnetic fields. However, there are important patterns of smaller-scale fields on the Sun—plage and supergranulation—that carry a large fraction of the global magnetic flux, and are present even at cycle minimum when few or no spots are on the disk. Just as the spots are associated with elevated chromospheric and coronal emissions (in the surrounding active region), so too are plage and the supergranulation network areas of enhanced chromospheric and transition region emissions. For this reason, such areas show very large intensity contrasts in the ultraviolet, even though they are not easily distinguishable from the surrounding quiet photosphere at visible wavelengths.

There are two basic approaches that one might utilize to determine the migration patterns of active regions, plage, and supergranulation in the chromospheric and transition-region emissions of stars. The first is to obtain direct narrow-band images (like *TRACE* does for the Sun) at very high spatial resolution; the second is to use high-resolution spectroscopy to measure Doppler shifted signatures of active regions in time series of emission line profiles (so-called Doppler Imaging).

HST, which has about 50 milliarcsecond resolution in the mid-UV [Gilliland & Dupree1996], has successfully imaged in chromospheric light only star, α Ori. Even though the angular size of the chromosphere of a cool giant star can significantly surpass that of the photosphere—the diameter of Betelgeuse in Mg II 2800 Å light is four times larger than its optical size [Uitenbroeck et al.1998]—the direct imaging of stellar outer atmospheres is a daunting task. In fact, to obtain a 100×100 pixel^2 UV map of the closest solar-like dwarf stars (sufficient to record small active regions and crudely image the supergranulation network) requires a spatial resolution of about a tenth of a milliarcsecond, $500\times$ better than the best delivered by *HST.* Extending the sample to dwarfs within 100 pc would require *microarcsec* imaging. Reaching such an objective might seem to be far in the future. Nevertheless, one promising concept under study at the NASA GSFC is the *Stellar Imager* mission, a kilometer scale interferometer composed of ~ 30 small telescopes formation-flying in space [Carpenter et al.2004].

Emission–Line Doppler Imaging, on the other hand, is a powerful contemporary tool for probing high-contrast surface structure or extended atmospheric zones in cool stars, strongly complementing optical and X-ray imaging which preferentially maps the dark spotted areas, and the corona, respectively. The reader is referred to Lanza98 and Rice02 for the techniques to derive photospheric images, and to the reviews by [Güdel2004] and [Favata & Micela2003] for X-ray imaging techniques. Here we discuss chromospheric and TR Doppler imaging methods. Discrete features moving through the line profile, say, chromospheric Mg II h&k 2800 Å or higher temperature C IV 1548 Å, can trace the locations of bright emission regions on the stellar surface, and help us understand how the activity is organized spatially and its relation to the dark starspots seen in optical Doppler images. A few maps of the chromospheres of RS CVn-type stars with rotation periods less than 3 days have been obtained by monitoring the Mg II h&k lines with *IUE* [Walter et al.1987, Neff et al.1989a, Busà et al.1999, Pagano et al.2001]. In this way, cool prominences have been found at distances of 1–2 stellar radii, implying that multi-temperature plasmas thread the circumstellar environments of these systems. Spatially resolved surface fluxes in the chromospheric plage maps suggested that these regions are sites of "saturated heating" [Linsky1991] and that the relationship between radiative and magnetic flux densities valid for the Sun cannot be extrapolated to these extremely active stars [Schrijver & Zwaan2000]. A related phenomenon is that of "super-rotational" broadening seen in the TR lines of certain types of rapidly-rotating giant stars. The observed line widths are up to twice that expected from the photospheric $v \sin i$, demonstrating that 100 000 K material is present at levels up to 10 pressure scale heights above its equilibrium altitude, raising questions as to how the gas got there and how it can remain [Ayres et al.1998].

From a practical point of view, Doppler imaging typically requires spectral resolution $\geq 30\,000$ (< 10 km s^{-1}) to detect discrete emission components migrating through the line profile. An additional requirement is the ability to obtain a time series of spectra with sufficient cadence to avoid smearing the Doppler information, and long enough coverage to distinguish between persistent surface features and transient flare activity. In fact, the best targets for emission-line Doppler imaging are rapidly-rotating stars, and these by their nature are highly active and flare frequently. For example, the single attempt by *HST* to map a cool-star outer atmosphere, namely HD 155555 [Dempsey et al.2001], covered one stellar rotation, and was only partially successful because flaring and non phase-dependent variability could not be separated from rotational modulation of unchanging active regions.

Another, more subtle, way to gain information on the small scale geometrical organization of a stellar atmosphere is to utilize fluorescent lines of molecules and atomic species. The molecular features further are a guide to the presence of very cool gas in the outer atmosphere, perhaps due to so-called molecular cooling catastrophes [Ayres1981]. Fluorescent lines of molecules (e.g., H_2 and CO) and atomic species (e.g., Fe I & II , O I , Cl I) are particularly strong in T Tauri stars (owing to their disks) and in red giants (owing to the generally tenuous atmospheres and the presence of "clouds" of very cool gas at high altitudes). For example, Her2002 (Her2002, Her2004) identified 146 emission lines of H_2 pumped primarily by Lyα in a STIS spectrum of the T Tauri star TW Hya. The fluorescent processes rely on the excitation of specific low-excitation lines by wavelength-coincident radiation fields produced in hotter, spatially separated regions of the stellar (or disk) atmosphere. In the case of the red giants, the dominant pumping lines are the resonance transitions of atomic oxygen and hydrogen, and the hot chromospheric layers in which these radiations form are too far removed from the cooler photosphere to properly excite the observed fluorescent transitions, at least if one considers traditional 1-D thermal models for such objects. The implication is that hot and cold gas are much more intimately associated in the outer atmospheres of these stars. It might be that magnetic processes (which tend to produce filamentary hot structures in an otherwise cool atmosphere) are more important in the red giants, for example, than previously thought; and that, in turn, might be an indication that the winds of such stars could have a magnetic origin. In short, fluorescent processes can be a guide to the geometrical organization of a stellar atmosphere (or accretion disk) on small physical length scales not accessible to direct telescope observations.

In this connection, it should also be mentioned that studies of the atmospheres of close-in exoplanets, through Doppler shifted Lyα and other fluorescence emissions, could be feasible with a sufficiently-sensitive next-generation UV spectrometer.

3.1.2 Velocity fields and plasma dynamics

The heart of understanding chromospheric and coronal heating—one of the major unsolved problems in solar and stellar physics—is mechanical energy transport and dissipation. In the outer convection zone, immediately beneath the photosphere, turbulence transforms gas kinetic energy into sound waves and propagating electrodynamic disturbances. Given the difficulty of transmitting sound waves through the steep TR temperature gradient, electrodynamic processes are thought to provide the bulk of coronal heating. However, the shock dissipation of pure acoustic waves probably is an important heating source for nonmagnetic portions of the chromosphere and the lower transition region. How sizeable this contribution is with respect to the magnetic mechanisms is not yet understood (c.f., Judge and references therein), and the quantitative details of the energy transport and dissipation processes remain elusive. What is clear, however, is that plasma dynamics is an important byproduct of the heating mechanisms, and thus a potential window into their nature.

Observations of the Sun (e.g., Teriaca and references therein) and late-type stars (e.g., Ayres83, Ayres88, Wood97, Pagano04) have shown that transition region emission lines are, on average, redshifted, and that the redshifts increase with increasing formation temperature up to about 10^5 K. This behaviour is not anticipated by models of upward propagating acoustic waves, for which both optically thin (e.g., Han93, Wiketal00) and optically thick lines [Carlsson & Stein1997] are predicted to be blueshifted. On the other hand, statistically the observed solar redshifts are largest over active regions (Bri; Peter00), compared with quiet areas [Achour et al.1995]; and some TR models [Reale et al.1996] predict larger redshifts in regions permeated by strong magnetic fields than in quiet regions.

The maximum redshift ($\sim$15 $\mathrm{km\,s^{-1}}$) is reached at about 1-1.2$\times10^5$ K (active regions and quiet Sun, respectively). At higher temperatures, the centroid velocities decrease, crossing over to blueshifts at T$\sim10^6$ K (reaching about $\sim$–10 $\mathrm{km\,s^{-1}}$). A similar behaviour is seen in α Cen A [Pagano et al.2004], α Cen B [Wood et al.1997], ϵ Eri [Jordan et al.2001], and Procyon [Wood et al.1996], although the latter shows a maximum redshift at somewhat higher temperatures [Wood et al.1997]. On the other hand, the TR lines of the very active dM1e star AU Mic show hardly any redshifts, and certainly show no conspicuous trend of line shift versus formation temperature (Pagano00 & Redfield).

In addition to redshifts, stellar transition region emission lines also show a curious bimodal structure. AU Mic (dM1e) was the first star for which this behaviour was noticed [Linsky& Wood1994]. The authors found that the Si IV and C IV lines have broad wings superimposed on a narrower central peak. The same bimodal structure of Si IV and C IV lines subsequently was detected in TR spectra of other stars covering a range of spectral types, luminosity classes, and activity levels, from RS CVn-type systems (e.g., HR 1099), to main sequence dwarfs (e.g., AU Mic, Procyon, α Cen A and B), and giants (Capella, 31 Com, β Cet, β Dra, β Gem, and AB Dor) [Linsky et al.1995, Pagano et al.2000, Linsky& Wood1994, Vilhu et al.1998, Pagano et al.2004]. The broad components have widths comparable to, or wider than, the broadened C IV profiles observed in solar transition-region explosive events (see Dere), small bursts thought to be associated with reconnections of emerging magnetic flux to overlying pre-existing canopy fields. Wood97 showed that the narrow components can be produced by turbulent wave dissipation or Alfvén wave-heating mechanisms, while the broad components—whose strength correlate with activity indicators like the X-ray surface flux—can be interpreted as a signature of "microflare" heating. Alternatively, for the particular case of rapidly rotating AB Dor, Vilhu suggested that broad wings can arise from a ring of hot gas at 2–3 stellar radii, like the "slingshot prominences" seen in Hα.

Using *SoHO*/SUMER data, Peter showed that broad components are a common feature in the thermal regime 40 000 K to 10^6 K above the magnetically dominated chromospheric network. The author presented evidence that the narrow line core and broad wings are formed in radically different physical settings: small closed loops and coronal funnels, respectively, the latter being the footpoints of large coronal loops. Non-thermal widths of the broad components follow a power-law distribution with respect to line-formation temperature, a signature of upward propagating magneto-acoustic waves [Peter2001]. In stars other than the Sun, the broad components have been observed over formation temperatures of 40 000 K to 2×10^5 K.

Usually, chromospheric emission lines do not show broad wings in time-averaged spectra of normal stars, although very optically thick, opacity-broadened features like the Mg II h&k resonance lines would tend to mask such components if present. However, in extremely active stars, or during large stellar flares, chromospheric broad components occasionally are seen. For example, transient broad *redshifted* components of Mg II were recorded in the RS CVn binary AR Lac during a large flare event early in the *IUE* mission by LinskyN-eff. In another active binary, HR 1099, Busa suggested that persistent broad components observed in Mg II h&k were associated with a large active region close to the pole. Subsequently, Lanzafame employed a two-component NLTE model to synthesize the stellar Hα and Mg II h&k lines, demonstrating that the broad component could be explained as an effect of elevated densities in the active region, while the narrow component would be formed in the surrounding lower density quiet chromosphere. This conceptually is a much different model than the dynamical origin proposed for the optically thin TR lines, but still potentially is a valuable indicator of local plasma conditions in active regions. Future observational and theoretical studies are needed to determine which is the more realistic model.

Extending the observational side of plasma dynamics to higher, coronal temperatures is relatively straightforward on the Sun, because many suitable strong coronal permitted lines (e.g., Mg X 610,25 Å) fall in the Lyman continuum region immediately below 912 Å, where high-resolution far-UV spectroscopy still is practical. Unfortunately, these key features are not accessible even in the nearest stars owing to interstellar extinction. Observing spatially-resolved profiles of permitted coronal X-ray lines, say in the important iron-L shell band at ~1 keV, is not feasible at present, because contemporary high-energy missions like *Chandra* and *XMM*–Newton have inadequate spectral resolution by an order of magnitude, and there are no planned future missions that will push that limit.

However, a number of coronal *forbidden* lines in the UV range longward of the Lyman continuum edge have been observed in the Sun (see for example Doschek, Feldman00). On the stellar side, *HST*'s GHRS and STIS instruments, and *FUSE,* have been able to detect highly ionized iron forbidden lines in many cool stars (see for example Maran, Pagano00, Ayres03a, Redfield03) with high spectral resolution (up to R = 40 000).

The UV coronal forbidden lines detected in cool stars for the most part show negligible Doppler shifts from the photospheric radial velocities, suggesting that the emissions arise mainly from confined structures, analogous to magnetic loops on the Sun, rather than from a hot wind. Moreover, the Fe XII and Fe XXI line widths generally are close to their thermal values (FWHM 40–90 km s^{-1} at $T\sim10^{6.2}$–$10^{7.0}$ K), except for the Hertzsprung-gap giants 31 Com (G0 III) and Capella (G1 III) and the K1 IV component of HR 1099, all of which display excess broadening in Fe XXI. If the additional broadening is rotational, it would imply that the hot coronae of "X-ray deficient" 31 Com and Capella are highly extended, compared to the compact structures suggested by recent density estimates in a number of active coronal sources. On the other hand, the more common case of purely thermal line widths implies that supersonic turbulent motions are absent in the coronal plasma, eliminating shock waves as an important heating mechanism.

3.1.3 The physics of impulsive heating: stellar flares and microflares

Flares, lasting from a few minutes to several days, are the most dramatic examples of transient energy release in solar and late-type stellar atmospheres. A magnetic reconnection process is thought to power these events: magnetic free energy is converted—in thin current sheets—into thermal heating, Alfvén waves, and the acceleration of relativistic particles. Accordingly, the relaxation phenomenon is complex and fast, producing radiation across the whole electromagnetic spectrum from nonthermal radio synchrotron, to thermal emissions in the UV and X-ray ranges. In fact, the flare phenomenon involves the whole atmosphere, from the corona down to the lower chromosphere and photosphere, which are blasted by hard radiations and particle beams from the high-altitude flare kernel [Haisch et al.1991]. The investigation of detailed flare physics historically has relied on multiwavelength simultaneous observations, involving both spectroscopy and photometry.

Ultraviolet emission lines provide an important source of plasma cooling, as well as lower-atmospheric heating, during the gradual phase of stellar flares (e.g., Hawley03), and thus are valuable diagnostics of the flare evolution. Fig. 2 shows Mg II h & k line profiles from a flare on the RS CVn-type binary HR 1099 observed by *IUE*. At the flare peak, the Mg II lines display very broad wings, and the mid-UV continuum is enhanced. Busa analysed this flare and concluded that material was ejected by the secondary star in the direction of the primary.

Although large flares are a conspicuous contributor to transient heating of stellar coronae, smaller scale events—so-called micro- and nano-flares—might play a key role in the "steady" heating of the outer layers of cool stars. Robinson studied the statistics of transient bursts in high time resolution UV observations of AU Mic with *HST* STIS, and concluded that the power-law slope of the occurrence rate versus time-integrated flux was considerably steeper for low-energy flares than for the rarer high-energy ones; implying that microflares potentially can account for a significant portion, if not all, of the coronal heating (see, e.g., Hudson and Gudel2003). However, this is such an important issue that more conclusive evidence is needed: the investigation should be extended to a larger sample of flare stars with sufficient time resolution and sensitivity to collect a significant number of events for each target.

3.1.4 UV emissions from very late M dwarfs and brown dwarfs

Magnetic activity decreases for spectral types later than approximately M7. However, flares have been observed in the radio, optical, UV and X-rays from very late dM stars and brown dwarfs (e.g., Linsky95, Rutledge). Several authors have suggested that hot gas in the atmospheres of very low mass main-sequence stars and brown dwarfs is present only during flares (Fleming, Rutledge, Mohanty, Berger). However, by recording UV spectra of a sample of these stars, HJ-K showed that persistent quiescent chromospheres and transition regions, similar to those observed in earlier type dMe's, are present at least through spectral type M9. The existence of persistent magnetic activity in these fully convective stars poses challenges for contemporary $\alpha\Omega$-type dynamo models that require a shear layer between the convective outer envelope and the radiative interior. The current thinking is that a "distributed dynamo" might be in play, one that operates directly on convective turbulence and does not require the catalyzing agency of differential rotation. Incidentally, this same "α^2" dynamo process probably also is operating in the slowly rotating red giants, to account for the feable, but nonetheless present, coronal activity of the inhabitants of the so-called "coronal graveyard" [Ayres et al.2003b], i.e. the region of the HR diagram near K1 III where stars were rarely detected in coronal proxy C IV (T $\sim 10^5$ K) lines and in X-ray surveys.

Extending this work—transient vs. persistent hot plasma—to the even lower mass range, and much cooler atmospheres, of the brown dwarfs will require significantly more sensitive UV spectroscopy than was available, for example, from *HST* STIS.

3.1.5 Composition anomalies in stellar outer atmospheres

Observations of solar and stellar coronae and of the solar wind provide evidence for plasma chemical composition anomalies with respect to the photosphere. The most famous of these is the so-called First Ionization Potential (FIP) effect: elements with low FIP (I.P.$<$10 eV) are overabundant with respect to high-FIP ($>$10 eV) species, relative to photospheric ratios. This is the case, for instance, in closed magnetic flux regions on the Sun and in the slow solar wind (see FL2000 for a review). On stars, a variety of behaviours are found, including the absence of any low-FIP bias, normal low-FIP enhancements, and even low-FIP abundance depletions (the so-called Metal Abundance Depletion [MAD] syndrome) seen in very active stars [Audard et al.2003, Güdel2004].

The FIP chemical fractionation effect is thought to be a byproduct of the processes that heat and structure the chromosphere. For example, MHD waves passing through an ambient plasma with a temperature below about 7000 K, where low-FIP elements are the only ones ionized, could selectively sweep these ions into the corona, thereby boosting the local abundance. An important goal for future work would be to link stellar chromospheric spatial structure, as derived from UV Doppler images, to the coronal abundance patterns deduced from rotational modulations of suitable coronal X-ray lines, to constrain models of the FIP effect and its MAD syndrome cousin.

Recently, Laming2004 has proposed models for abundance anomalies in the coronae of the sun and other late-type stars following a scenario first introduced by Schwadron1999. According to these models, the abundance anomalies are produced by the pondermotive (proportional to the $\mathbf{j}\times\mathbf{B}$) force on ions arising as Alfvén waves propagate through the chromosphere and depends sensitively on the chromospheric wave energy density. The model can explain both the solar FIP effect and its variations as well as the inverse FIP effect observed in some stars. A better understanding of the coronal abundance anomalies may therefore offer a unique diagnostic of Alfvén wave propagation between the chromosphere and corona.

3.2 Magnetic activity of stars hosting planets

More than 130 extrasolar planets have been detected so far, mainly around solar-type stars. Most of these planets are massive Jovian–types, observationally favored by the currently popular Doppler-reflex observing techniques. However, space missions like *COROT* [Baglin2003], *Kepler* [Borucki et al.2003], and *Darwin* [Fridlund2004] will discover—and eventually allow us to characterize—Earth-sized extrasolar planets.

How a planet might directly interact with its parent star is a new field of research, motivated by the tight orbits of some of the extreme "roasters." CSM predicted that a giant planet orbiting close-by a star incites increased stellar activity by means of tidal and magnetospheric interactions. Experimental data supporting this prediction were reported by Shkolnik (Shkolnik, Shkolnik05), who found the strength of the emission reversals in the Ca II H&K lines of a couple of stars hosting *hot jupiters* to be variable with the planet's orbital period. The effects of the nearby planet should be exaggerated in the upper chromosphere, transition region, and corona; thus UV, and EUV, spectroscopy will certainly contribute importantly to exploring such planet-star interactions.

The other side of the story is to understand how stellar activity affects planets, especially habitable ones. The evolution of a planetary atmosphere under the joint erosive impacts of coronal ionizing radiations and wind from the parent star (e.g., A97), is an exciting scientific issue, with important ramifications for understanding the evolution of Earth's paleoclimate and the birth of life (see Lammer).

UV spectroscopy of the parent stars of planetary systems is feasible with a 2-m class telescope for most of the relatively nearby stars in contemporary planet searches by the Doppler reflex technique, as shown by *HST*. In fact, by using STIS on *HST*, VM03 found $\sim$15$\pm$4% extra-absorption in the Ly–α emission line of HD 209458 (V=7.6) during the transit of its *hot–jupiter* planet, which can be understood in terms of escaping hydrogen atoms from the planet atmosphere. Again looking at the UV stellar spectrum during the planetary transit, VM04 detected C and O in the atmosphere of HD 209458b. However, a more sensitive 4–6-m class UV facility would be needed to reach the next tier of fainter planet-stars that will be discovered in future surveys by *COROT* and *Kepler* exploiting the transit method.

In terms of detecting life on other worlds, we mention that there are useful biomarkers in the UV: for example ozone, O_2, H_2, CO^+, CH_4. Gómez de Castro et al. in this volume has a more extensive description of these biomarkers, so we will not discuss them further.

3.3 Astrospheres and solar-like stellar winds

Winds of late-type stars are a byproduct of magnetic coronal activity, certainly in dwarf stars like the Sun, but perhaps also, to some extent, in red giants (e.g., Ayres03b). The winds of low-mass cool stars feed back on their coronal evolution owing to the significant angular momentum carried away by a fast, magnetized outflow. In the evolved red giants, winds can potentially change the nuclear evolution of the star by removing significant mass from the surface layers (see e.g. RHHW). Furthermore, as mentioned previously, coronal winds can erode volatiles from primitive planetary atmospheres by sweeping up charged molecules and ions from exospheric regions ionized by the stellar UV radiation field. Hence, exploring the winds of low-mass and evolved stars is of fundamental importance from a number of standpoints.

The velocity structure, mass loss rate, and ionization of the outflowing gas in the low-temperature ($\sim 10^4$ K) winds of late-type giants and supergiants can be inferred from high resolution spectra of optically thick UV resonance lines (see e.g. Dupree2004, Young2005, Dupree05). The UV provides unique access to the dominant circumstellar wind absorption species in the red giants: H I, O I, Mg II, and C II. Unfortunately, the winds of main sequence stars like the Sun are too hot and too thin to provide detectable UV or X-ray absorption (or emission) signatures, yet understanding these coronal outflows is of paramount importance to the wide range of issues described above. Fortunately, however, in a few favorable cases of nearby stars, coronal winds can be studied by subtle distortions of the H I Lyα line due to the "hydrogen walls" produced by the interaction of the stellar outflow with inflowing interstellar gas (cf. Wood01, Wood05a). In the stellar "astrosphere", the stellar analog of the solar "heliosphere", decelerated interstellar hydrogen (in the stellar rest frame) produces an absorption feature on the blue side of the interstellar absorption (seen in the observer's rest frame), as shown in Fig. 3. By modeling these absorption features, Wood02 performed the first quantitative measurements of mass loss rates for G and K dwarf stars. These authors found that the mass loss rates increase with activity, as measured by the X-ray surface flux, and thus with decreasing stellar age. By extending their investigation on a slightly larger sample of dwarfs, Wood05b found evidence that winds suddenly weaken at a certain activity threshold. These authors suggest that in very active stars, winds may be inhibited by the strong magnetic fields associated with stellar spots that have a large filling factor on these stars. The sample of dwarfs for which an astrosphere has been detected thanks to high resolution profiles of their H I Lyα lines consists of 14 stars only. While it is necessary to significantly enlargen the number of studied stars in order to sample with a great significance each activity/age stage, the mass–loss/age relation inferred by Wood05b gives us an empirical estimate of the history of the solar wind. By implication, the solar wind might have been 1000 times stronger when the Sun was very young, and thereby likely played a major role in the evolution of planetary atmospheres, particularly the stripping of volatiles from primitive Mars.

3.4 Activity in young stellar clusters

The study of late-type stars in young ($\sim 50 - 100$ Myr) galactic clusters, and even younger star-forming regions (1-10 Myr), is a valuable window into not only the evolution of magnetic activity, but also its basic characteristics. In particular, within a given cluster or other coeval group of objects, the relationships between, for example, activity indicators and rotation periods for stars of different spectral types will not suffer a hidden age bias due to the common age and chemical composition of the stars.

It is generally accepted that late-type stars undergo spin-down due to magnetic braking throughout their main-sequence phase, especially near the beginning when their angular momentum is highest thanks to spin-up by their natal disks (see, e.g., JC93; CJ94 and references therein). Studies of the "Sun in time" (see Ribas2005, GRH03, A97, and references therein) have made use of observations of stars with different rotation periods and ages, but spectral types similar to the Sun to build a scenario of what might have happened to the Sun at different stages along its evolutionary path. These several efforts have used observations of activity tracers in the optical, ultraviolet and X-rays. In particular, in the ultraviolet domain *IUE* spectra were intensively exploited to extract information on chromospheric and transition region fluxes; while more recently *FUSE* observations were used to study the outer atmosphere [Guinan et al.2003]: emission features in the *FUSE* 920–1180 Å band probe hot plasma over three decades in temperature: from $\sim 10^4$ K for the H I Lyman series to $\sim 6 \times 10^6$ K for the coronal Fe XVIII 974 Å line.

The general activity-rotation-age relationship in stars also has been the subject of many studies. In one of the first efforts, [Simon et al.1985] utilized *IUE* data of a moderate size sample of solar-type field stars, compared with observations of T Tauri stars, in order to determine whether the pattern of main-sequence chromospheric decay shown by stars older than about 100 Myr extended back to earlier times. They showed that the activity-age relation for main sequence stars older than about 100 Myr can be modeled by an exponential law whose rate of decline depends on surface temperature.

Unfortunately, few subsequent extensive studies in this direction have been carried out using the much more sensitive contemporary instruments of *HST* or other missions. A99 obtained GHRS spectra (1150–1670 Å) of three solar-type dwarfs in the young clusters α Per (85 Myr) and the Pleiades (125 Myr) to complement an earlier FOS study of 10 cluster stars, including 5 in the Hyades (625 Myr); with the aim to investigate the behavior of the stellar activity and the dynamo at early ages [Ayres1997]. Although the study drew important conclusions on the activity-age relationship for TR lines like C IV, these referred specifically to early G-type dwarfs, and generalization to other spectral types and luminosity classes was not possible. The lack of modern UV studies of the age-activity relation contrasts with the very extensive surveys accomplished in the optical (see e.g. SJF01) and X-ray domains. In the latter, for example, Piz03 investigated the relationship between coronal X-ray emission and stellar rotation in a sample of 259 dwarfs in the $B-V$ range 0.5–2.0 observed with *ROSAT*, including 110 field stars and 149 members of the Pleiades, Hyades, α Per, IC 2602 (30 Myr) and IC 2391 (30 Myr) open clusters. The "missing" UV part of the puzzle is extremely important to problems such as the radiative erosion of primitive planetary atmospheres by young hyperactive parent stars because the dominant ionizing radiations for abundant atmospheric molecules like N_2 fall in the Lyman continuum (see A97); the crucial bright O v 629 Å feature, for example, cannot be observed directly in stars, but its strength can be inferred through measurements of O iv, O v, and O vi UV lines longward of the 912 Å H i edge.

At ages less than about 10^7 years, pre-main sequence T Tauri stars are located in star-forming regions. The UV is extremely valuable in studies of the less-obscured classical and "naked" T Tauri stars. For example, Her2004 has studied the fluorescent excitation of the Lyman bands of H_2 lines by H i Lyα to probe the physical conditions in the accretion disk. UV signatures of the hot splashdown point of the accretion stream can be exploited to estimate the accretion rate and geometry [Johns-Krull et al.2000, Calvet et al.2004]. Furthermore, these very young objects, not surprisingly, are hyperactive in terms of the usual UV and X-ray indicators, and thus provide a laboratory for "magnetic activity in extreme environments". The dissection of the highly complex TRs and coronae of these quite exotic objects is an important challenge for future emission-line Doppler imaging efforts.

4 Instrument requirements

Progress in exploring fundamental cool-star issues such as the dynamo and coronal heating benefits tremendously from high resolution UV spectroscopy. At a minimum, a resolution of R= 30 000 is sufficient to resolve most of the narrow chromospheric emission lines seen in dwarf stars, which typically have FWHM >10 km/s. The hotter TR lines are broader owing to higher thermal velocities, but they also benefit from good resolution for deblending purposes, dynamical studies, and Doppler imaging. In addition to resolution, high sensitivity is needed to reach the faint, interesting objects beyond the solar neighborhood, out to at least 150 pc to include, for example, the important young galactic clusters α Per and the Pleiades, as well as the key TW Hya star-forming region.

For studies of cool winds and astrospheres, higher resolutions are needed: $R = 100\,000$ has proved crucial in previous GHRS and STIS work, and certain ISM-oriented problems probably could benefit from $R = 200\,000$, or more. Here, however, sensitivity is less of an issue, because most of the key objects for wind studies are nearby bright red giants (or bright hot stars for ISM work). For some sources the lack of short-term variability (particulary in the ISM background "light sources") means that one can integrate for long periods to build up sufficient signal-to-noise in the high-resolution line profiles.

It also would be important to have a high sensitivity mode at lower resolution, to reach the next tier of interesting objects beyond the horizon accessible to the $R = 30\,000$ mode and to study flares and other types of variability. Historically (e.g., for GHRS or STIS) this would be a R = 1 000 resolution mode, but we would argue for at least 3–5 000 (i.e., velocity resolution better than 100 km s^{-1}) because then one can have cleaner separation of close lines, some velocity discrimination in short-period binary systems, and the possibility of measuring hypersonic dynamics in large flare events. Furthermore, broad spectral coverage in the low-resolution and mid-resolution modes is essential, from the viewpoint of observing efficiency.

Together with point source spectroscopy, a long-slit imaging capability, in at least the low resolution mode (R=3-5 000) and possibly also the mid-resolution mode (R=35 000), would be especially valuable for studies of close binaries and the gaseous environments of PMS stars. In fact, a simple direct imaging system with suitable narrow-band filters tuned to important TR lines like C IV could be exploited to monitor flares and rotational modulations of active regions in dozens of late-type stars at the same time, for example, members of a compact galactic cluster or PMS candidates in a star-forming region. A beam splitter could divert visible light into a simple prism system that would record a low-resolution spectral energy distribution as well as key emission features such as Ca II or Hα. In this regard, the "Optical Monitor" on *XMM*–Newton has proven extremely valuable, although in the cool-star application one would want an optical system with a large dynamic range capable of recording bright nearby stars as well as much fainter distant objects.

In summary, research on cool stars would benefit enormously from a new 2m class orbiting telescope feeding a high sensitivity, high resolution UV spectrometer, with an auxilliary strap-on optical/UV monitoring system. The telescope should be placed far from the Earth in a drift-away, L2, or Molniya-type high orbit suitable for long-duration uninterrupted observations of targets to obtain high quality Doppler maps, flare light curves and statistics, and for operational flexibility to allow rapid response to targets of opportunity. High wavelength accuracy is required by many of the topics we would address, hence a Pt-Ne calibration system—missing from FUSE, but which has been incredibly valuable for GHRS and STIS—is an essential component of such a facility.

A larger aperture telescope, of 4–6m class, would permit the study of plasma dynamics and chromospheric/TR structures of fainter magnetic active stars, brown dwarfs, and cool stars in more distant stellar clusters and star-forming clouds beyond 150 pc. This more sensitive facility would also be able to characterize the outer atmospheres of parent stars of extrasolar planets that will be discovered by future space missions like *Corot, Kepler* or *Darwin.*

A summary of instrumental requirements discussed above is given in Table 1.

5 Conclusions

The term "stellar activity", as applied to the Sun and other late-type stars, includes a very broad range of phenomena, such as starspots, plages, active regions, prominences, flares, coronal loops, winds, mass ejections, and so forth. These phenomena are observed directly on the Sun, and their existence on other stars is inferred by solar analogy from specific spectral properties or behaviors (following the so-called "solar-stellar" connection).

The driving mechanism for stellar activity is the magnetic field generated presumably by a dynamo process at the base of or embedded in the convection zone. The activity that we see in the outer atmospheres of late-type stars thus has its roots deep within the star. This activity is important in its own right, and also because of the influences of its ionizing radiations and wind on the heliosphere, or its extrasolar equivalent; as a model of magnetodynamic processes operating broadly in the cosmos; and as a window into the deep interior of the star.

Since in the near future, direct surface imaging of the morphology connected with activity will not be feasible for other stars, the key information must be extracted from remote-sensing spectroscopy. The importance of the ultraviolet part of the electromagnetic spectrum in this regard has been emphasized: cool-star magnetic activity produces hot material above the stellar photosphere, from the chromosphere to the million degree, or hotter, corona. There are very few lines in the optical or infrared that are sensitive even to the cooler end of this range. On the other hand, emission lines formed at temperatures up to 10^7 K are accessible in the UV longward of the LyC edge, and achieving high spectral resolution and large effective areas is much more feasible in this wavelength domain than in soft X-rays. From a practical point of view, cool stars usually have negligible photospheric emission below $\sim$1900 Å, so the UV emissions from magnetically disturbed hot gas can be recorded with high contrast.

We can confidently say that ultraviolet astronomy is absolutely fundamental for understanding cool-star physics, and further progress in this area absolutely requires a new generation of UV observatories in space.

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References

[Achour et al.1995] Achour, H., Brekke, P., Kjeldseth-Moe, O., and Maltby, P.: 1995, *ApJ* 453, 945

[Audard et al.2003] Audard, M, Güdel, M., Sres, A., Rassen, A.J.J., and Mewe, R.: 2003, *A&A* 398, 1137

[Audard et al.2004] Audard, M. Telleschi, A., Güdel, M., Skinner, S.L., Pallavicini, R., and Mitra-Kraev, U.: 2004, *ApJ* 617, 531

[Ayres1981] Ayres, T R.; 1981, *ApJ* 244, 1064

[Ayres1997] Ayres, T.R.; 1997, *JGR (Planets)* 102, 1641

[Ayres1999] Ayres, T.R.; 1999, *ApJ* 525, 240

[Ayres2005] Ayres, T.R.; 2005, *"Astrophysics in the Far-Ultraviolet: Five Years of Discovery with FUSE,"* G. Sonneborn, W. Moos, and B.-G. Andersson (eds.), ASP Conference Series, in press

[Ayres et al.1983] Ayres, T.R., Stencel, R.E., Linsky, J.L., Simon, T., Jordan, C., Brown, A., and Engvold, O.: 1983, *ApJ* 274, 801

[Ayres et al.1988] Ayres, T. R., Jensen, E., & Engvold, O. 1988, *ApJS* 66, 51

[Ayres et al.1996] Ayres, T.R, Simon, T., Stauffer, J.R., Stern, R.A., Pye, J.P., and Brown, A.: 1996, *ApJ* 473, 279

[Ayres et al.1998] Ayres, T.R, Simon, T., Stern, R.A., Drake, S.A., Wood, B.E., and Brown, A.: 1998, *ApJ* 496, 428

[Ayres et al.2003a] Ayres, T.R, Brown, A., Harper, G.M., Osten, R.A., Linsky, J.L., Wood, B.E. and Redfield, S.: 2003a, *ApJ* 583, 963

[Ayres et al.2003b] Ayres, T.R, Brown, A., and Harper, G.M.: 2003b, *ApJ* 598, 610

[Baglin2003] Baglin, A.: 2003, *AdSpR* 31, 345

[Baliunas et al.1995] Baliunas, S.L., Donahue, R.A., Soon, W.H., Horne, J.H., Frazer, J., et al.: 1995, *ApJ*, 438, 269

[Belvedere et al.(1980a] Belvedere, G., Paternò, L., and Stix, M.: 1980a, *A&A* 86, 40

[Belvedere et al.1980b] Belvedere, G., Paternò, L., and Stix, M.: 1980b, *A&A* 88, 240

[Belvedere et al.1980c] Belvedere, G., Paternò, L., and Stix, M.: 1980c, *A&A* 91, 328

[Berdyugina & Tuominen1998] Berdyugina, S.V, and Tuominen, I., 1998, *A&A* 336, L25

[Berger et al.2001] Berger, E. et al.: 2001, *Nature* 410, 338

[Boggess & Wilson1987] Boggess, A. and Wilson, R.: 1987, *"Exploring the Universe with the IUE Satellite"*, Y. Kondo (ed.), Kluwer Academic Publishers, Dordrecht, p. 3

[Bonanno et al.2005] Bonanno, A., Elstner, D., Belvedere, G., and Rüdiger, G.: 2005, *AN* 326, 170

[Borucki et al.2003] Borucki, W.J., et al.: 2003, *SPIE* 4854, 129

[Bowyer et al.2000] Bowyer, S., Drake, J.J. and Vennes, S.: 2000, *ARA&A* 38, 231

[Brynildsen et al.1996] Brynildsen, N., Kjeldseth-Moe, O., and Maltby, P.: 1996, *ApJ* 462, 534

[Busà et al.1999] Busà, I., Pagano, I., Rodonò, M., Neff, J.E., and Lanzafame, A.C.: 1999, *A&A* 350, 571

[Butler1994] Butler, C.J.: 1994, *Sol. Phys.* 152, 35

[Calvet et al.2004] Calvet, N., Muzerolle, J., Briceño, C., Hernández, J., Hartmann, L. and Saucedo, J.L.: 2004, *AJ* 128, 1294

[Carlsson & Stein1997] Carlsson, M. and Stein, R.F.: 1997, *ApJ* 481, 500

[Carpenter et al.2004] Carpenter, K.G., Schrijver, C.J., Allen, R.J., et al.: 2004, *SPIE Astronomical Telescopes and Instrumentation*, SPIE Paper #5491_28

[Catalano et al.2000] Catalano, S., Rodonò, M., Cutispoto, G., Frasca, A., Marilli, E., et al.: 2000, in *Variable Stars as Essentil Astrophysical Tools*, C. Ibanoglu (ed.), NATO ARW, 544, p. 687

[Chugainov1966] Chugainov, P.F.: 1966, *Comm. 27 IAU, Inf. Bull. Var. Stars* 122

[Collier Cameron & Jianke1994] Collier Cameron, A. and Jianke, L.: 1994 *MNRAS* 269, 1099

[Cuntz et al.2000] Cuntz, M., Saar, S.H., and Musielak, Z.E.: 2000, *ApJ* 533, L151

[Cutispoto et al.2001] Cutispoto, G., Messina, S., and Rodonò, M.: 2001, *A&A* 367, 910

[Cutispoto et al.2003] Cutispoto, G., Messina, S., and Rodonò, M.: 2003, *A&A* 400, 659

[Dempsey et al.2001] Dempsey, R.C., Neff, J. E., and Lim, J.: 2001, *AJ* 122, 332

[Dere et al.1989] Dere, K. P., Bartoe, J.-D. F., and Brueckner, G. E.: 1989, *Sol. Phys.* 123, 41

[Doschek et al.1975] Doschek, G. A., et al.: 1975, *ApJ* 196, L83

[Dupree & Reimers1987] Dupree, A. K. and Reimers, D.: 1987, *"Exploring the Universe with the IUE Satellite"*, Y. Kondo (ed.), Kluwer Academic Publishers, Dordrecht, p. 321

[Dupree et al.2004] Dupree, A.K.: 2004, *IAU Symp.*, 219, 623

[Dupree et al.2005] Dupree, A.K., Lobel, A., Young, P.R., Ake, T.B., Linsky, J.L., and Redfield, S.: 2005, *ApJ* 622, 629

[Favata & Micela2003] Favata, F., and Micela, G.: 2003, *SSRv.* 108, 577

[Favata et al.2004] Favata, F., Micela, G., Baliunas, S.L., Schmidtt, J.H.M.M., Güdel, M., et al.: 2004, *A&A* 418, L13

[Feldman & Laming2000] Feldman, U., and Laming, J.M., 2000: *Phys. Scr.*, 61, 222

[Feldman et al.2000] Feldman, U., Curdt, W., Landi, E., and Wilhelm, K.: 2000, *ApJ* 544, 508

[Fleming et al.2000] Fleming, T.A., Giampapa, M.S., and Schmitt, J.H.M.M.: 2000, *ApJ* 533, 372

[Fridlund2004] Fridlund C.V.M.: 2004, *AdSpR* 34, 613

[Gilliland & Dupree1996] Gilliland, R.L., and Dupree, A.K.: 1996, *ApJ* 463, L29

[Godoli1968] Godoli, G.: 1968, in *Mass Motion in Solar Flares and Related Phenomena, 9th Nobel Symp.*, Y. Oehman (ed.), p. 211

[Güdel2004] Güdel, M.,: 2004, *A&ARv* 12, 71

[Güdel2003] Güdel, M., Audard, M., Kashyap, V.L., Drake, J.J., and Guinan, E.F.: 2003, *ApJ* 582, 423

[Guinan et al.2003] Guinan, E.F., Ribas, I. and Harper, G.M.: , 2003 *ApJ* 594, 561

[Haisch et al.1991] Haisch, B., Strong, K.T., and Rodonò, M.: 1991, *ARA&A* 29, 275

[Hansteen1993] Hansteen, V.: 1993, *ApJ* 402, 741

[Harper2004] Harper, G.M.: 2004, *Proc. of the "13th Workshop Cool Stars, Stellar Systems and the Sun"*, F. Favata et al. (eds), ESA SP-560, p.51

[Hawley et al.2003] Hawley, S.L., et al.: 2003, *ApJ* 597, 535

[Hawley & Johns–Krull2003] Hawley, S.L., and Johns–Krull, C.M.: 2003, *ApJ* 588, L112

[Herczeg et al.2002] Herczeg, G.J., Linsky, J.L., Valenti, J.A., Johns-Krull, C.M., and Wood, B. E.: 2002, *ApJ* 572, 310

[Herczeg et al.2004] Herczeg, G.J., Wood, B.E., Linsky, J.L., Valenti, J.A., and Johns-Krull, C.M.: 2004, *ApJ* 607, 369

[Hudson1991] Hudson, H.S.: 1991, *Sol. Phys.* 133, 357

[Imhoff & Appenzeller1987] Imhoff, C. L. and Appenzeller, I.: 1987, *"Exploring the Universe with the IUE Satellite"*, Y. Kondo (ed.), Kluwer Academic Publishers, Dordrecht, p. 295

[Jianke & Collier Cameron1993] Jianke, L. and Collier Cameron, A.: 1993, *MNRAS* 261, 766

[Johns-Krull et al.2000] Johns-Krull, C.M., Valenti, J.A., and Linsky, J.L.: 2000, *ApJ* 539, 815

[Jordan & Linsky1987] Jordan, C. and Linsky, J.L.: 1987, *"Exploring the Universe with the IUE Satellite"*, Y. Kondo (ed.), Kluwer Academic Publishers, Dordrecht, p. 259

[Jordan et al.2001] Jordan, C., Sim S.A., McMurry, A.D., and Aruvel, M.: 2001, *MNRAS* 326, 303

[Judge et al.2004] Judge, P. G., Saah, S.H., Carlsson, M., and Ayres, T.R.: 2004, *ApJ*, 609, 392

[Laming2004] Laming, J.M., 2004: *ApJ*, 614, 1063

[Lammer et al.2003] Lammer, H., Selsis, F., Ribas, I., Guinan, E. F., Bauer, S.J., and Weiss, W.W. 2003: *ApJ*, 598, L121

[Lanza et al.1998] Lanza, A.F., Catalano, S., Cutispoto, G., Pagano, I., and Rodonò, M.: 1998, *A&A* 332, 179

[Lanza et al.2002] Lanza, A.F., Catalano, S., Rodonò, M., Ibanoglu, Tas, G., et al.: 2002, *A&A* 386, 583

[Lanzafame et al.2000] Lanzafame, A.C., Busà, I., and Rodonò, M.: 2000, *A&A* 362, 683

[Linsky1991] Linsky, J.L.: 1991, *Mechanisms of Chromospheric and Coronal Heating*, P. Ulmschneider, E. R. Priest, & R. Rosner (eds.), (Berlin: Springer-Verlag), 166

[Linsky2003] Linsky, J.L.: 2003, *Adv. Space Res.* 32, 917

[Linsky et al.1995] Linsky, J. L., Wood, B.E., Judge P., Brown, A., Andrulis, C., and Ayres, T.R.: 1995, *ApJ* 442, 381

[Linsky& Wood1994] Linsky, J.L., and Wood: 1994, *ApJ* 430, 342

[Maran et al.1994] Maran, S.P., et al.: 1994, *ApJ* 421, 800

[Messina & Guinan2002] Messina, S., and Guinan, E.F.: 2002, *A&A* 393, 225

[Messina & Guinan2003] Messina, S., and Guinan, E.F.: 2003, *A&A* 409, 1017

[Messina et al.2001] Messina, S., Rodonò, M., and Guinan, E.F.: 2001, *A&A* 366, 215

[Messina et al.2002] Messina, S., Pizzolato, N., Guinan, E.F., and Rodonò, M.: 2002, *A&A* 410, 671

[Mohanty et al.2002] Mohanty, S., Basri, G., Shu, F., Allard, F., and Chabrier, G.: 2002, *ApJ* 571, 469

[Neff et al.1989a] Neff, J.E., Walter, F.M., Rodonò, M., and Linsky, J.L., 1989a, *Solar and Stellar Magnetic Activity*, Cambridge Astrophysics Series, 34

[Neff et al.1989b] Neff, J.E., Walter, F.M., Rodono, M., and Linsky, J.L.: 1989b, *A&A* 215, 79

[Osten et al.2003] Osten, R.A., Ayres, T.R., Brown, A., Linsky, J.L., and Krishnamurthi, A.: 2003, *ApJ* 582, 1073

[Olah & Strassmeier2002] Olah, K., and Strassmeier, K.G.: 2002, *AN* 323, 361

[Pagano et al.2001] Pagano, I., Rodonò, M., Linsky, J.L., Neff, J.E., Walter, F.M., Kovári, Zs., and Matthews, L.D.: 2001, *A&A* 365, 128

[Pagano et al.2000] Pagano, I., Linsky, J.L., Carkner, C., Robinson, R.D., Woodgate, B., and Timothy, G.: 2000, *ApJ* 432, 497

[Pagano et al.2004] Pagano, I., Linsky, J.L., Valenti, J., and Duncan, D.K: 2004, *A&A* 415, 331

[Pallé Bagó & Butler2001] Pallé Bagó, E., and Butler, C.J.: 2001, *IAU Symp.* 203, 602

[Paternò1998] Paternò, L.: 1998, *Compt. Rend. Acad. Sci. Paris*, Ser. IIb 326, 393

[Peter2000] Peter, H.: 2000, *A&A* 360, 761

[Peter2001] Peter, H.: 2001, *A&A* 374, 1108

[Pizzolato et al.2003] Pizzolato, N., Maggio, A., Micela, G., Sciortino, S. and Ventura, P.: 2003, *A&A* 397, 147

[Rauscher et al.2002] Rauscher, T., Heger, A., Hoffman, R.D., Woosley, S.E.: 2002, *ApJ* 576, 323

[Reale et al.1996] Reale, F., Peres, G., and Serio, S.: 1996, *A&A* 316, 215

[Redfield et al.2002] Redfield, S., Linsky, J.L., Ake, T.B., Ayres, T.R., Dupree, A.K., Robinson, R.D., Wood, B.E., and Young, P.R.: 2002, *ApJ* 581, 626

[Redfield et al.2003] Redfield, S., Ayres, T.R., Linsky, J.L., Ake, T.B., Dupree, A.K., Robinson, R.D., and Young, P.R.: 2003, *ApJ* 585, 993

[Ribas et al.2005] Ribas, I., Guinan, E.F., Güdel, M., and Audard, M.: 2005, *ApJ* 622, 680

[Rice2002] Rice, J.B.: 2002, *AN* 323, 220

[Robinson et al.2001] Robinson, R.D., Linsky, J.L., Woodgate, B., and Timothy G.: 2001, *ApJ* 554, 368

[Rodonò1986] Rodonò, M.: 1986, in *Fourth Cambridge Work. on Cool Stars, Stellar Systems and the Sun, Lecture Notes in Physics* 254, 475

[Rodonò et al.1995] Rodonò, M., Lanza, A.F., and Catalano, S.: 1995, *A&A* 301, 75

[Rodonò et al.2000] Rodonò, M., Messina, S., Lanza, A.F., Cutispoto, G., and Teriaca, L.: 2000, *A&A* 358, 624

[Rodonò et al.2002] Rodonò, M., Cutispoto, G., Lanza, A.F., and Messina, S.: 2002, *AN* 322, 333

[Rutledge et al.2000] Rutledge, R.E., Basri, G., Martn, E.L., and Bildsten, L. 2000: *ApJ* 538, L141

[Schrijver & Zwaan2000] Schrijver, C.J. and Zwaan C.: 2000, *ApJ* 473, 470

[Schwadron et al.1999] Schwadron, N.A., Fisk, L.A., and Zurbuchen, T.H., 1999, *ApJ* 521, 859

[Simon et al.1985] Simon, T., Herbig, G. and Boesgaard, A.M.: 1985, *ApJ* 293, 551

[Shkolnik et al.2001] Shkolnik, E., Walker, G.A.H., and Bohlender, D.A.: 2001, *AAS* 33, 1303

[Shkolnik et al.2005] Shkolnik, E., Walker, G.A.H., Bohlender, D.A., Gu, P.-G., and Kürster, M.: 2005, *ApJ* 622, 1975

[Soderblom et al.2001] Soderblom, D., Jones, B.F. and Fisher, D.: 2001, *ApJ* 563, 334

[Strassmeier1990] Strassmeier, K.G.: 1990, *ApJ* 348, 682

[Strassmeier et al.1991] Strassmeier, K.G., Rice, J.B., Welhau, W.H., Vogt, S.S., Hatzes, A.P., et al.: 1991, *A&A* 247, 130

[Strassmeier et al.1997] Strassmeier, K.G., Bartus, J., Cutispoto, G., and Rodonò, M.: 1997, *A&AS* 125, 1

[Uitenbroeck et al.1998] Uitenbroek, H., Dupree, A.K., and Gilliland, R.L.: 1998, *AJ* 116, 2501

[Teriaca et al.1999] Teriaca, L., Banerjee, D., and Doyle, J.G.: 1999, *A&A* 349, 636

[Vidal-Madjar et al.2003] Vidal-Madjar, A., Lecavelier des Etangs, A., Désert, J.-M., Ballester, G.E., Ferlet, R., Hébrard, G., and Mayor, M.: 2003, *Nature* 422, 143

[Vidal-Madjar et al.2004] Vidal-Madjar, A., Désert, J.-M., Lecavelier des Etangs, A., Hébrard, G., Ballester, G.E., Ehrenreich, D., Ferlet, R., McConnell, J.C., Mayor, M., and Parkinson, C.D.: 2004, *ApJ* 604, 69

[Vilhu et al.1998] Vilhu, O., Muhli, P., Huovelin, J., Hakala, P., Rucinski, S.M., and Collier Cameron, A. 1998, *AJ* 115, 1610

[Walter2003] Walter, F.M.: 2003, *The Future of Cool-Star Astrophysics: 12th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun*, A. Brown, G.M. Harper, and T.R. Ayres (eds.), p. 14

[Walter et al.1987] Walter, F.M., Neff, J.E., Gibson, D.M., et al., 1987, *A&A* 186, 241

[Wamsteker & González-Riestra1998] Wamsteker, W. and González-Riestra, R. (eds.) *Proc. of the Conference "Ultraviolet Astrophysics beyond the IUE Final Archive"*, ESA SP-413

[Wikstøl et al.2000] Wikstøl, Ø., Hansteen, V.H., Carlsson, M., and Judge, P. G.: 2000, *ApJ* 531, 1150

[Wilson1978] Wilson, O.C.: 1978, *ApJ* 26, 379

[Wood et al.1996] Wood, B.E., Harper, G.M., Linsky, J.L., and Dempsey, R.C.: 1996, *ApJ* 458, 761

[Wood et al.1997] Wood, B.E., Linsky, J.L., and Ayres, T.R.: 1997, *ApJ* 478, 745

[Wood et al.2001] Wood, B.E.,Linsky, J.L., Müller, H.-R., and Zank, G.P.: 2001, *ApJ* 547, L49

[Wood et al.2002] Wood, B.E., Müller, H.–R., Zank, G.P., and Linsky, J.L.: 2002, *ApJ* 574, 412

[Wood et al.2005a] Wood, B.E., Redfield, S., Linsky, J.L., Muller, H.-R., and Zank, G.P: 2005, *ApJS*, 159, 118

[Wood et al.2005b] Wood, B.E., Müller, H.–R., Zank, G.P., Linsky, J.L., and Redfield, S.: 2005, *ApJL*, 628, 143

[Young et al.2005] Young, P.R., Dupree, A.K., Espey, B.R., Kenyon, S.J., Ake, T.B.: 2005, *ApJ*, 618, 891

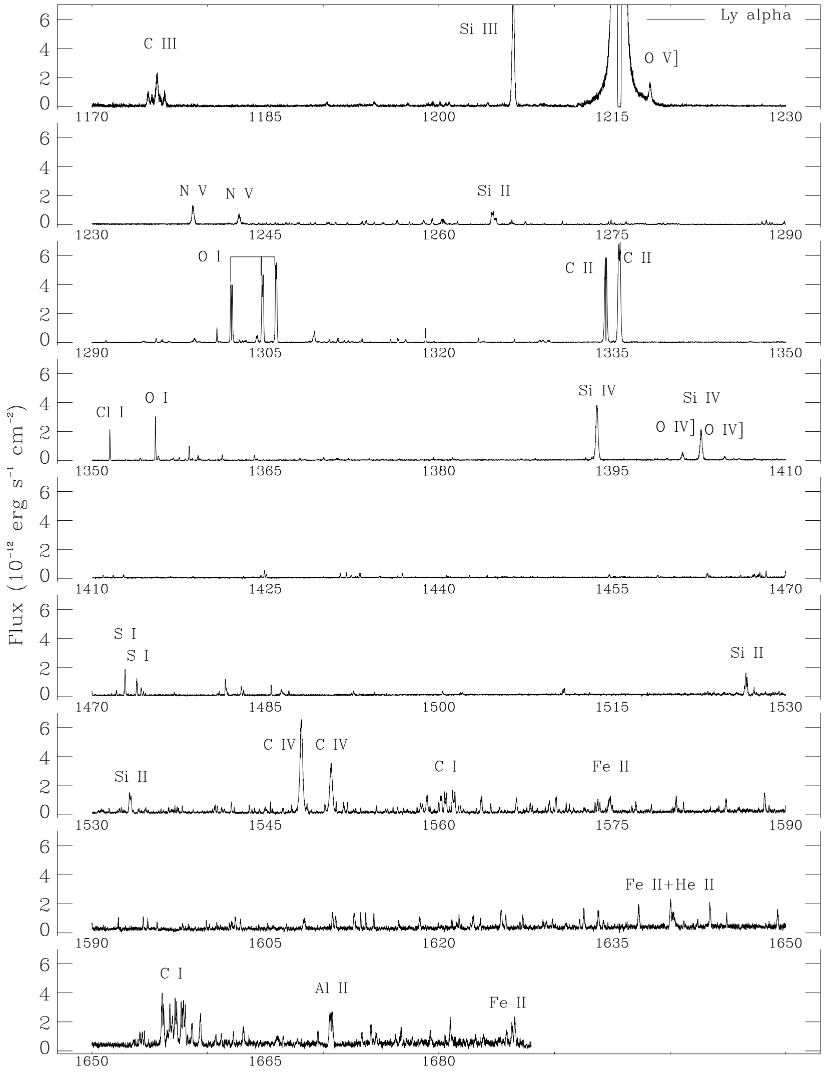

Figure 1: The spectrum of α Cen A, a twin of the Sun, as observed by *HST*/STIS. Only the strongest transitions are labelled. This spectrum contains a wealth of emission lines that probe the stellar atmosphere from the chromosphere to the coronae (from Pagano et al. 2004).

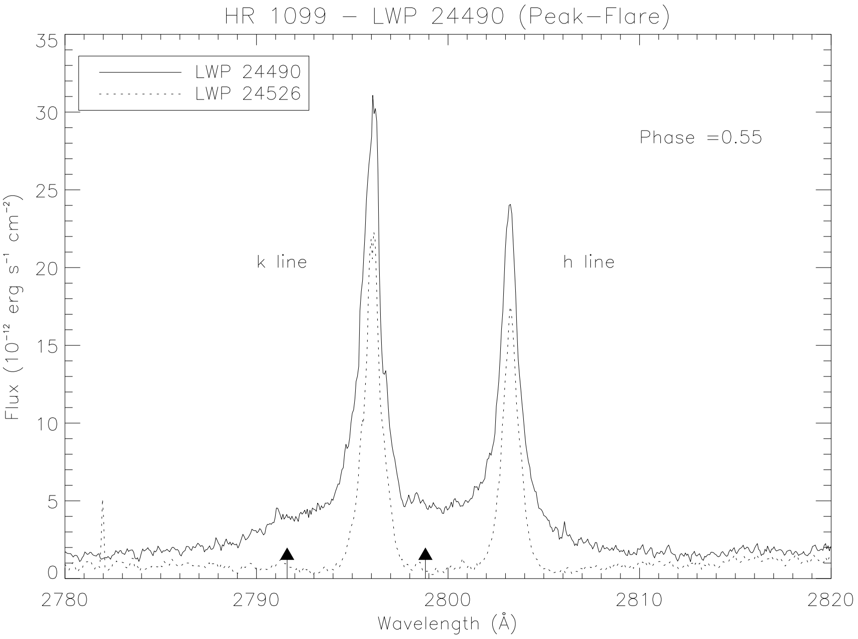

Figure 2: A very strong flare of the RS CVn-type system HR 1099 observed in the Mg II h&k lines by *IUE*. The dotted line is a spectrum obtained during quiescence. Arrows indicate the Mg II $3d-3p$ subordinate lines (from Busà et al. 1999)

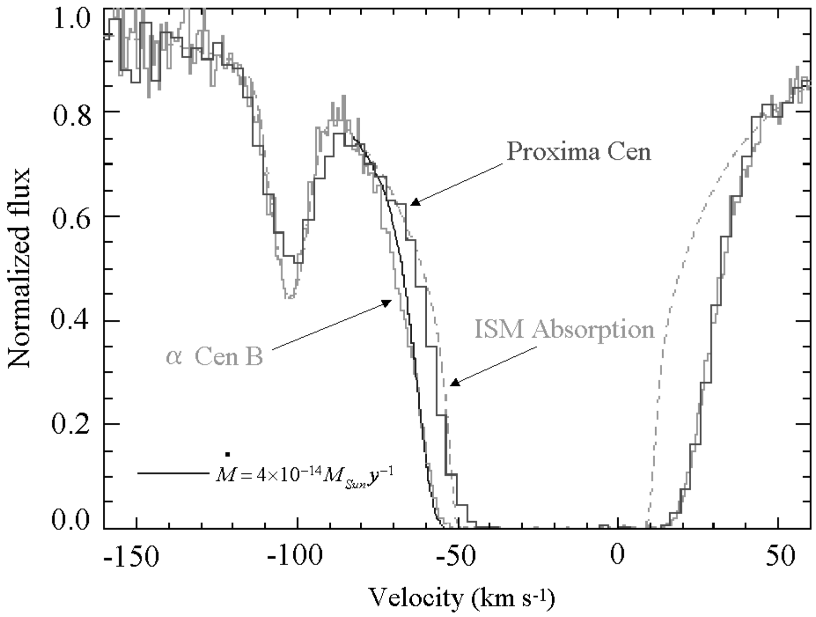

Figure 3: Comparison between the Lyα spectra of α Cen B (grey-tone histogram) and Proxima Cen (black-tone histogram). The inferred ISM absorption is shown as a grey-tone dashed line. The α Cen/Proxima Cen data agree well on the red side of the H I absorption, but on the blue side the Proxima Cen data do not show the excess absorption seen toward α Cen (i.e., the astrospheric absorption). The blue-side excess Lyα absorption is fitted by a model of the α Cen astrosphere, corresponding to a mass loss of $\dot{\rm M}$=4×10^{-14} $M_\odot$ y^{-1} (adapted from Wood et al 2001).

Table 1: Instrumental requirements for research on cool stars in the UV domain

Issue	**Telescope** class	**S**pectroscopy or **I**maging	**Spectral Resolution**	**Spatial Resolution**	**Monitoring**	**Time resolution**
Doppler Imaging of field stars	2m	S	$\geq$35 000		YES	minutes
Direct Imaging of chromospheres and TRs	Interferometry (e.g. 20 $\times$1m)	I		$\sim$50–100 μas	YES	minutes
Plasma dynamics in chromosphere, TR and corona	2m	S	$\geq$35 000		YES	minutes
Stellar activity of extrasolar planets' parent stars	2m 4–6m^a	S	$\geq$35 000		YES	minutes
Astrospheres & solar like stellar winds	2m 4–6m^a	S	$\geq$100 000		YES	minutes
Flares	2m	S	>10 000		YES	seconds

a) targets that will be explored by *COROT*, *Kepler*, and *Darwin*.