PART 1

INFRARED DIAGNOSTICS OF THE SOLAR ATMOSPHERE AND SOLAR ACTIVITY

THE COLD HEART OF THE SOLAR CHROMOSPHERE

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Abstract. The early 1990's heralded the deployment of vastly improved space instruments in the ultraviolet (HST) and X-ray (ROSAT) bands, where thermal inhomogeneities in high-excitation chromospheres and coronae are seen in their most favorable light. The infrared spectrum provides a key complementary view of inhomogeneities, but only recently has begun to be seriously exploited for studies of the solar chromosphere and the outer atmospheres of other late-type stars.

Key words: infrared: stars – molecular processes – stars: chromospheres – stars: coronae – Sun: atmosphere

1. Introduction

Thermal inhomogeneities are a fact of life in the high-excitation outer atmospheres of late-type stars. The existence of severe contrasts in plasma conditions from point to point in the chromosphere and higher-altitude layers provides a strong motivation — and an endless source of frustration — for observers and theorists alike. On the one hand, the dazzling array of fine structure in the outer atmosphere of the Sun challenges the creativity of solar observers, faced with the daunting prospect of trying to resolve sub-arcsecond features from the ground; on the other hand it cruelly tantalizes stellar physicists who can record only the disk-average spectra of their subjects. Furthermore, theorists would prefer to work with spherically-symmetric, laterally-homogeneous models, rather than the messy reality of the solar chromosphere-corona.

Nevertheless, the inhomogeneous character of stellar outer atmospheres is not simply a trivial annoyance that Nature foists upon us; rather it is the fundamental signature of the heating and cooling processes that give rise to the decidedly non-classical high-altitude layers. A clear understanding of the heretofore elusive energization mechanisms requires a concerted effort to dissect the physical properties of the inhomogeneities. That effort necessarily must be rooted in the ultraviolet and higher-energy emissions that form preferentially in the heated gas. At the same time, infrared studies — particularly of low-excitation species like molecules — can shed light on the ambient atmosphere in which the chromospheric and coronal structures are embedded. The contrasting — and sometimes outwardly inconsistent — pictures must be reconciled in order to obtain a complete description of the inhomogeneous solar outer atmosphere; and to provide potential spectral diagnostics for the far less tractable, but equally important, stellar case.

Those of you expecting a detailed discussion of solar inhomogeneities will be disappointed because I will focus here mostly on stars. Those of you who are expecting an extensive treatise on carbon monoxide — my favorite toxic molecule — also will be disappointed because I will focus primarily on wavelengths other than the infrared and species other than molecules. And, those of you expecting a comprehensive review of the literature will be disappointed as well, because I will focus on some very new results that have not yet been submitted for publication. The general theme of my presentation is that we find ourselves in an exciting time,

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where the advent of new instruments – particularly the space-borne variety like HST and ROSAT – are providing an unprecedented view of stellar chromospheres and coronae. The infrared promises equally dramatic advances when the present technical revolution in panoramic detectors and cryogenic grating spectrometers moves from the instrument shops into the solar (and night-time) observatories.

2. The RIASS Coronathon

No solar physicist would challenge the statement: "The solar outer atmosphere is thermally inhomogeneous." Ground-based Ca II filtergrams and FUV/X-ray images taken from satellites and sounding rockets provide incontrovertible proof that the solar chromosphere-corona is dominated by strong contrasts in temperature and density on very fine spatial scales. Nevertheless, other stars cannot be resolved in the same direct way as the Sun, so the evidence in favor of solar-like structures is largely circumstantial.

In conjunction with the all-sky X-ray survey performed by the Röntgensatellit (ROSAT) between August 1990 and January 1991, there was a major effort to explore the empirical properties of stellar coronae in a large, minimally-biased sample of late-type stars. A cooperative observing program ("RIASS") between the International Ultraviolet Explorer (IUE) and the ROSAT all-sky survey team resulted in contemporaneous far-UV spectroscopy (primarily of the crucial C IV λ1550 emission) and 0.1–2.4 keV soft X-ray detections of about fifty carefully-chosen "coronal" stars (Ayres *et al.*, 1992). Figure 1 illustrates a correlation diagram depicting the dependence of the high-excitation coronal flux on the lower-excitation transition-zone (TZ) emission. X-ray upper limits are represented by the smaller symbols.

The solar-type (F9 and later) main-sequence and subgiant stars generally follow a 3/2 power law between their coronal and TZ emissions (*cf.* Ayres, Marstad, and Linsky, 1981), although the mid-F stars appear to deviate from the main trend somewhat (cf., Simon and Drake, 1989) and are deficient in low-activity objects. Our Sun would appear near the bottom of the MS distribution. The ordinary giants (luminosity class III) display a more complicated behavior. The cooler giants (G3 and later) tend to follow a 3/2 power law like that of the MS stars; but many of the warmer giants – virtually all $\approx 2 - 3\mathcal{M}_{\odot}$ Hertzsprung-gap stars – fall on a secondary relation displaced about an order of magnitude in $\mathcal{R}_{\rm X}$ below the MS line: this is the "X-ray deficiency" described by Simon and Drake (1989). It is also worth noting that despite the relatively normal (*i.e.*, MS-like) behavior of the G3–K0 giants, the archetype red giant Arcturus (α Boo: K1 III) falls at least two orders of magnitude below the MS trend (based on a nondetection in an 18.6 ks ROSAT pointing reported by Ayres, Fleming, and Schmitt [1991]; and a marginal detection of C IV in a coadded IUE spectrum totalling about 18.9 ks of exposure.) Arcturus is significant because it represents a surrogate for the distant future of the low-mass stars ($\mathcal{M} \lesssim 1\mathcal{M}_{\odot}$) in general, and our Sun in particular. Most of the other class-III giants in the diagram are more massive ($\mathcal{M} \gtrsim 2\mathcal{M}_{\odot}$), and have evolved from progenitors that were A- and B-type stars on the MS.

The late-type supergiants (luminosity classes I and II) seem to follow the same "X-ray deficient" trend as the Hertzsprung-gap giants; correction for reddening

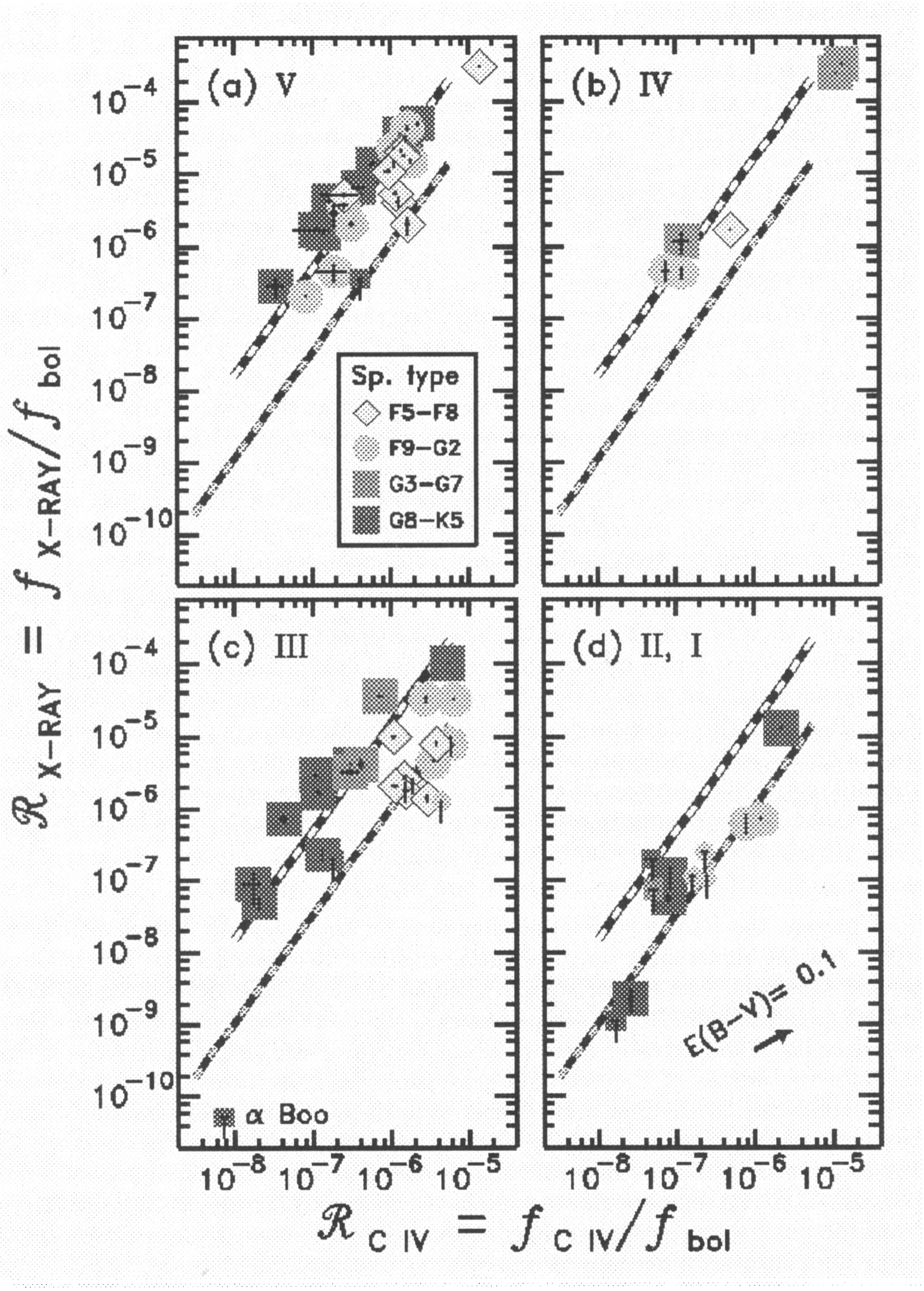

Fig. 1. Correlation diagram from RIASS "Coronathon".

would move the luminous stars even further away from the MS line. The supergiants all are massive objects ($\mathcal{M} \gtrsim 5\mathcal{M}_\odot$) which only recently have moved into the cool half of the H–R diagram from the upper main sequence (O- and B-types), although most probably are crisscrossing on "blue loops" of their convoluted evolutionary trajectories. The RIASS diagram is significant, because for the first time it directly compares two classes of supergiants that previously were considered unrelated. On the one hand are the "overactive" yellow supergiants like β Cam (G0 Ib) and β Dra (G2 Ib) which are strong coronal X-ray and FUV emission sources; on the other hand are the so-called "hybrid" supergiants (*e.g.*, Hartmann, Dupree, and Raymond, 1980) that show much weaker C IV emission and evidence for significant mass-loss as deduced from their red-asymmetric chromospheric Mg II features. Prior to ROSAT, there was only a marginal detection of coronal X-rays from the optically-brightest hybrid — α Triangulum Australae (K2 IIb-IIIa) — by EXOSAT (Brown *et al.*, 1991). The hybrids were considered unusual at the time of their discovery because signatures of coronal emission (namely the proxy C IV) and mass-loss are essentially mutually exclusive among the red giants (Linsky and Haisch, 1979). Arcturus is a case in point. Now, however, the sensitive ROSAT survey has revealed that the two types of supergiants fall on the same X-ray/C IV trend, suggesting a deeper connection between their ostensibly disparate coronal properties.

I don't want to make too much of the existence of two distinct X-ray/C IV relations: I've already gotten into trouble with other kinds of bifurcations! Possibly one is witnessing the operation of two different modes of the hydromagnetic "dynamo" (*e.g.*, Parker, 1970). One mode likely applies to MS stars such as the Sun that are moderate-to-fast rotators with relatively deep convective envelopes; the other mode likely applies to stars that either are fast rotators with shallow convective layers (like the Hertzsprung-gap giants), or slow-to-moderate rotators with deep convection zones (like the supergiants in general).

I present the RIASS correlation diagrams for their didactic value: to impress upon you the remarkable range of the normalized X-ray and C IV fluxes found among MS stars. The former runs over about three decades from the quiet G/K dwarfs to hyperactive RS CVn-type binaries, while the latter runs over more than two decades. The ranges increase to seven and three decades, respectively, if one includes the depths of the "coronal graveyard" (*i.e.*, Arcturus). The X-ray and C IV emissions on the Sun arise almost exclusively in magnetic structures, from the network bright points to large-scale active regions. The surface coverage by the major source of quiet-Sun emission — the network elements — is only a few percent. Thus, it seems natural to explain the enormous increase in $\mathcal{R}_{\rm X}$ and $\mathcal{R}_{\rm C\,IV}$ from the quiet to active stars simply in terms of an increased surface coverage of some fundamental "quantum" of activity, say magnetic flux tubes. Compelling as the notion is, the fact that the power law connection between X-rays and C IV is *steeper* than unity suggests the quantum itself changes character in the more active stars, perhaps owing to an increasing dominance of active regions at the expense of the network.

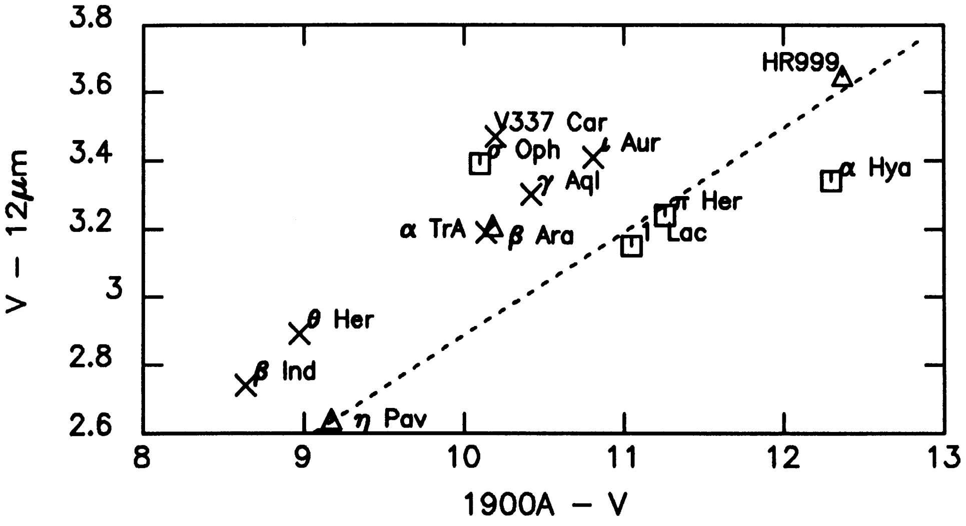

Fig. 2. IRAS/IUE two-color diagram for the "hybrid" (crosses) and normal (symbols) K bright giants. Bluer UV colors are to left.

3. The IRAS/IUE Connection

One of my students, R. B. Burton, has determined narrow-band colors at 12 μm and 1900 Å for more than 400 late-type stars observed by both the Infrared Astronomical Satellite and the International Ultraviolet Explorer. Our original motivation was to ferret out previously unknown warm companions of luminous cool stars, exploiting the extreme thermal leverage provided by the widely separated wavelength bands, and the high precision and consistency of the spacecraft-measured photometric indices.

One intriguing group with regard to the IRAS/IUE connection are the hybrid chromosphere bright giants, which I mentioned previously. Several years ago I noticed that the archetype hybrid — α TrA — has a surprisingly bright 1900 Å continuum in IUE spectra compared to the normal K-giant Arcturus, which has similar optical colors. I speculated that the UV excess was the result of a previously unseen F-type MS companion, and that some of the curious "hybrid" aspects of α TrA might be due to its putative binary nature (Ayres, 1985).

Burton's (1992) new study has raised serious doubts concerning my previous interpretation, by demonstrating that – among homogeneous groups of stars ranging from the K bright giants to the RS Canum Venaticorum binaries – the 1900 Å continuum excess shows a positive correlation with activity (measured by $\mathcal{R}_{\rm C\ IV}$ for example). Figure 2 illustrates that most of the hybrids have a significant UV excess with respect to "normal" K bright giants (dotted curve); Figure 3 demonstrates that most of the hybrids are overactive as well. Burton interprets the continuum excess to be due to the photospheric emission of active regions, which very likely are

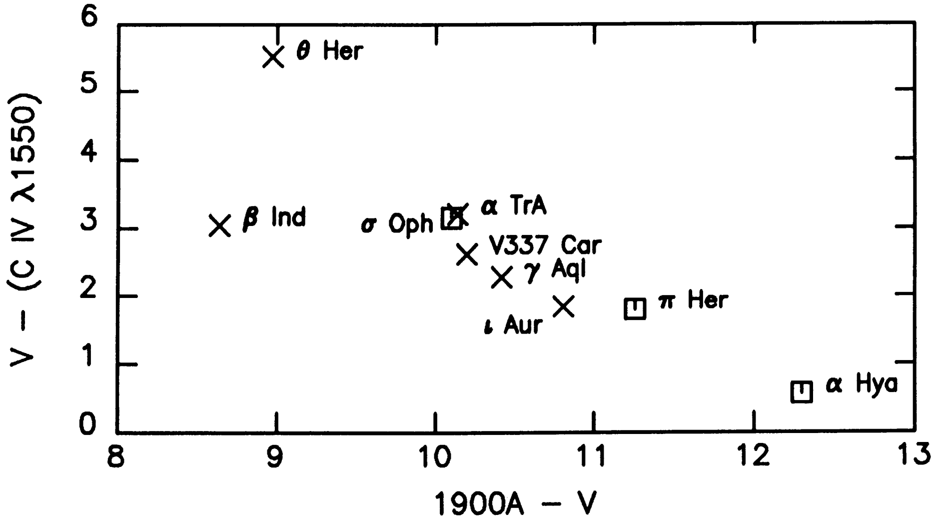

Fig. 3. Correlation of enhanced C IV emission with UV color excess.

warmer at mid-photospheric altitudes (where the 1900 Å continuum arises) than the undisturbed atmosphere. If true, the 1900 Å emission (easily recorded by the IUE) potentially can serve as a proxy measure of the surface coverage by facular areas, thereby providing a new indirect diagnostic for chromospheric inhomogeneities on other stars. Here, again, the shortwavelength emission has proved to be the superior tracer of chromospheric inhomogeneities, while the infrared has served primarily as a pivot for the UV thermal lever.

4. CO in the Sun

I already have discussed solar carbon monoxide *ad nauseam* in recent reviews (*e.g.*, Ayres, 1990, 1991) and do not wish to belabor the issue. In short, the excessively dark cores of the strong mid-IR (4.8 μm) $\Delta v = 1$ lines of CO close to the solar limb indicate the presence of remarkably cool material at high altitudes, probably well within the chromosphere itself. The fundamental question for those of us studying chromospheric inhomogeneities is how pervasive the cool component might be, and what role it plays in the energy balance of the outer atmosphere.

If cool gas occupies a significant volume of the chromosphere above the height of the traditional $T_{\rm min}$, then simulations of the energy balance of those layers based on conventional chromospheric thermal profiles can be very misleading. In particular, if much of the "action" that ultimately results in chromospheric emission occurs on small spatial scales, while the bulk of the remaining atmosphere is essentially passive, then homogeneous treatments of the radiative energy balance derived from spatially-averaged spectra will be triply wrong: initially in the empirical evaluation of surface fluxes; secondly in the inference of the temperature-pressure stratification

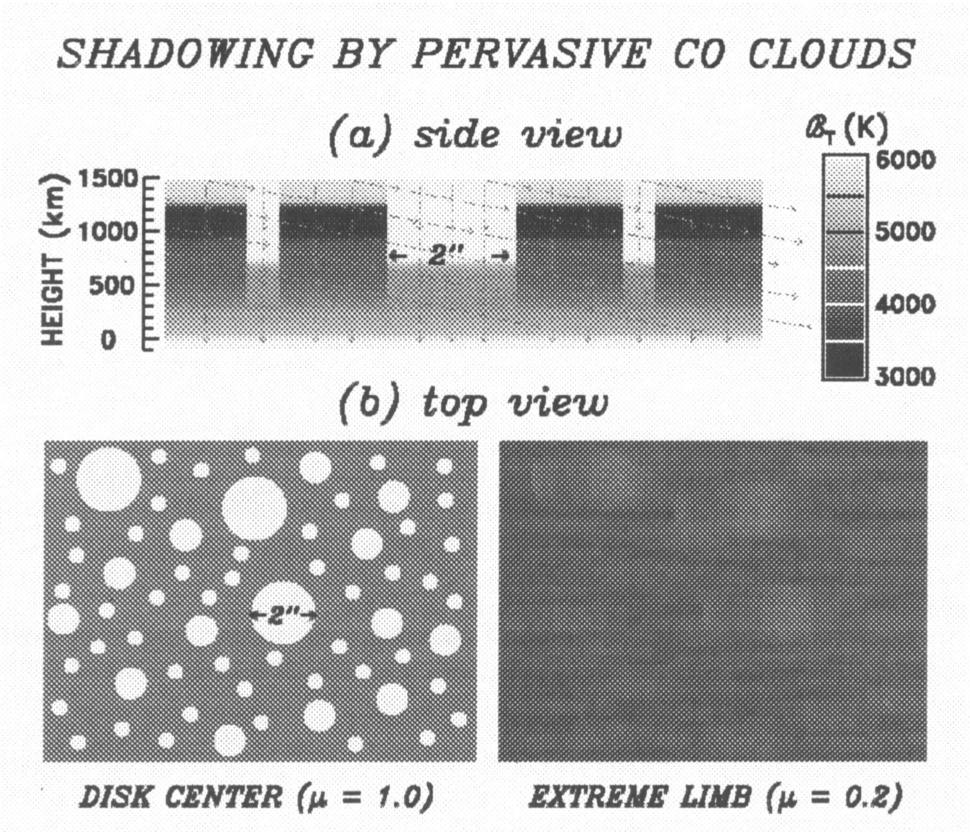

Fig. 4. Thermal models (panel [a]) and 2-D RT simulations (panel [b]) for the classical thermal bifurcation scenario: sparsely-distributed hot columns embedded in a cool near-RE matrix. The pervasive (75% coverage) cool component has a high-altitude *cloud* of very cold gas, above which is a steep rise of temperature into the chromospheric "canopy". In panel (b) the simulated spectroheliogram is for the strong 3–2 R14 line. The limb view was corrected for foreshortening to emphasize the *shadowing* phenomenon.

of the chromosphere; and finally in the numerical evaluation of the net radiative losses, from which the mechanical heating function is derived.

The existing studies of the solar 4.8 μm bands have had little or no spatial resolution and thus cannot resolve the issue directly. Ca II and CN filtergrams, as well as sounding-rocket images of the 1600 Å continuum, reveal a general *bright-point* character to the chromosphere, but are not sensitive to the cool component. I have conducted a series of 2-D radiative transfer experiments to assess the ability of the strong CO $\Delta v = 1$ lines to probe the conditions in the "cool clouds" (see Ayres, 1991). Figure 4 depicts the scenario I believe to be true, namely a chromosphere composed of small-scale bright points embedded in an otherwise cool "cloud deck" itself sandwiched between the warm photosphere (up to 500–600 km) and the hot chromospheric "canopy" ($\approx$ 1300 km). However, the simulations suggest that *shadowing* by even a small amount of CO in the chromosphere can overwhelm any hot material for limb lines of sight. Thus, we can reliably deduce the *thermal profile* of the cool component from the limb spectrum of the CO 4.8 μm bands, but not its *filling factor*.

The issue will remain controversial until the surface of the Sun is imaged directly in the CO fundamental lines. The NSO McMath main spectrograph currently is being reconfigured to carry a large IR grating that will be capable — in conjunction with the NSO infrared camera — of obtaining definitive stigmatic spectra of the 4.8 μm bands with diffraction-limited spatial resolution. The engineering project is scheduled for completion in 1992.

5. CO in the Stars

Studies of the Sun always will transcend those of other stars in technical sophistication, because the brightness of our stellar neighbor makes practical many kinds of instrumentation that would utterly fail in the low light conditions of night-time astronomy. Nevertheless, the nature of chromospheric inhomogeneities is not likely to be divined solely from the one example presented us by the Sun, just as a single slice of a biological specimen cannot qualify as a thorough dissection.

The history of stellar observations of the 4.8 μm CO bands is relatively brief, owing to the lack of sensitivity of current spectrometers. The instrument of choice has been the 1.4-m FTS at the NOAO Mayall 4-m telescope on Kitt Peak. One of the most important studies with the 4-m FTS also was one of the first: the observation by Heasley *et al.* (1978) of the archetype red giant Arcturus. The lack of chromospheric emission reversals in the deep CO absorptions — contrary to the predictions of the best-available models — prompted the authors to propose a multi-component scenario in which only 25% of the outer atmosphere was truly chromospheric; the remaining 75% was allotted to a cool (extended) photosphere in radiative equilibrium. The Heasley *et al.* observation was one of the original motivations for the "thermal bifurcation" hypothesis I introduced a few years later (Ayres, 1981). Unfortunately, Arcturus was about the only normal late-type star bright enough in the thermal IR to be recorded successfully by the Mayall FTS.

In the past few years, cryogenically-cooled spectral isolators — pioneered by the balloon instrumentation group at the NASA Goddard Space Flight Center (D. Jennings, D. Deming, G. Wiedemann, and colleagues) — have extended the effective sensitivity of the Mayall FTS dramatically. For his thesis work, Wiedemann (1989) was able to obtain high-resolution, high-S/N 4.8 μm spectra of a number of late-type giants and a few dwarfs and subgiants. Figure 5 illustrates some of the better examples. A theoretical basis for the analysis of such spectra has been given by Wiedemann and Ayres (1991). Notice, for example, the lack of measurable CO absorption in the F-type subgiant Procyon; the increased complexity of the CO spectrum in the four giants compared with the Sun; and the somewhat shallower and narrower absorptions of β Gem compared with α Boo and α Tau (the spectrum of α Aur is similar to that of β Gem, when the nearly featureless spectrum of the fast-rotating secondary star [F9/G0] is subtracted).

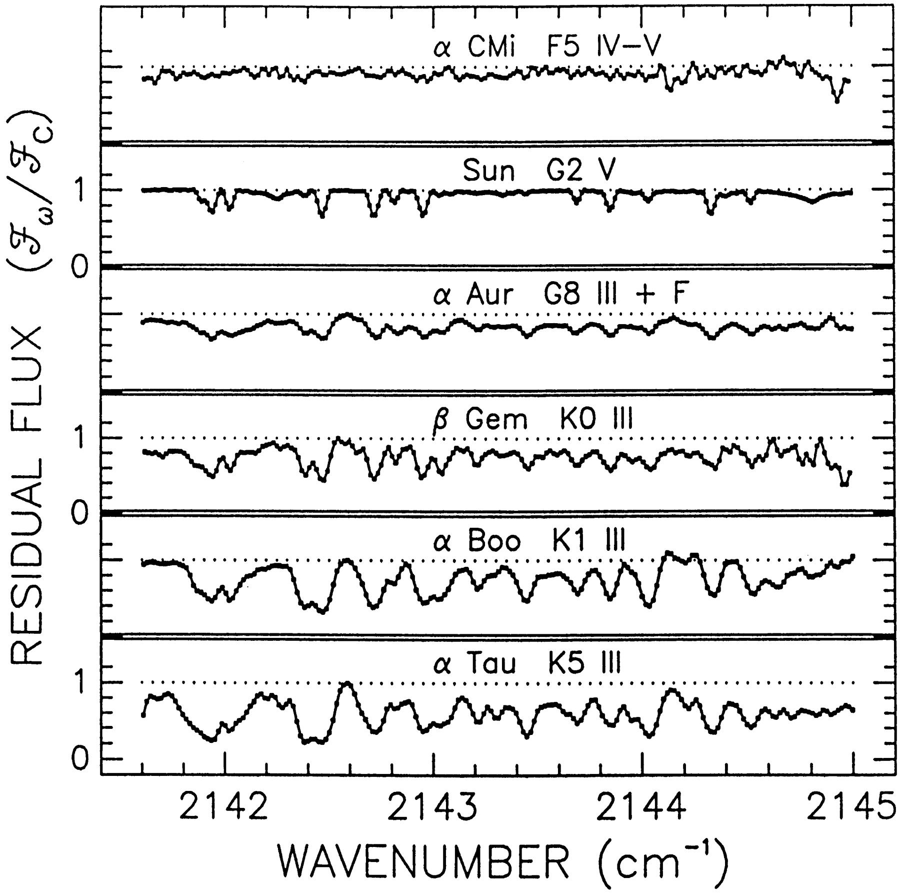

Fig. 5. Residual flux spectra of CO $\Delta v = 1$ bands in bright late-type stars.

The lack of CO absorptions in Procyon is consistent with the numerical simulations of Muchmore and Ulmschneider (1985) which indicate that the CO "cooling catastrophe" I proposed in the 1981 paper will not develop in stars with effective temperatures only a few hundred degrees warmer than the Sun. The additional complexity of the red-giant spectra compared with that of the Sun is due to the strengthening of the secondary isotopic bands, $^{13}C^{16}O$ and $^{12}C^{18}O$, in the chemically-evolved atmospheres. In fact, the isotopic richness of the CO spectrum of α Aur suggests that the slow-rotating primary is a post-helium-flash "clump" giant, rather than a "first-crosser" like the secondary star. Finally, the small but significant differences between the CO spectra of the coronal giant β Gem and the two noncoronal red giants probably are a symptom of a more pervasive cool "neophotospheric" component in the less active stars.

The results of Wiedemann's work are tantalizing, but unfortunately the number of objects accessible even with the Goddard postdisperser on the Mayall FTS (or other FTS's like that at the Canada-France-Hawaii Telescope) is quite limited: the prospects for broad surveys like those performed in the FUV and X-ray bands are dim. However, new stellar instruments promise to eclipse the FTS-era studies. The vanguard of the new generation are cryogenically-cooled grating spectrographs coupled with IR cameras. A good example is the "CSHELL" recently introduced at the NASA Infrared Telescope Facility. Others are under development at NOAO, ESO, GSFC, and elsewhere. While the resolving power of the grating instruments still is a factor of two below the $\omega/\Delta\omega \approx 80,000 - 100,000$ considered desirable for dwarf-star work, a vast array of problems can be attacked in the giant and supergiant regions. Furthermore, the impetus towards higher resolving powers, driven by studies of surface magnetism (*e.g.*, Saar, these proceedings) and circumstellar velocity fields (*e.g.*, Tsuji, 1988), will inevitably bring the dwarf stars within reach as well.

6. Conclusions

An old Chinese curse succinctly describes the present state of astronomy: "May you live in interesting times." Today's revolution in instrumentation across the entire electromagnetic spectrum far surpasses that of a decade ago when the likes of IUE, *Einstein*, IRAS, the VLA, and the M&M FTS's (McMath and Mayall) provoked a period of "paradigm perestroika" in our conceptions of the nature of chromospheric and coronal activity and their underlying physical inspiration. Some of the discoveries from the new generation of instruments are just beginning to appear, particularly on the more mature fronts of UV and X-ray astronomy. Nevertheless, the rapid pace of technical progress in the thermal infrared promises an equally glowing future in studies of the complementary aspects — like the CO clouds — of solar and stellar inhomogeneities.

I close by reiterating the conclusion of the review I gave in Heidelberg two years ago: A major future innovation would be the construction of a general-purpose large-aperture infrared solar telescope to permit high spatial resolution studies of the dynamics and evolution of surface structure and embedded magnetic activity. A group at the National Solar Observatories, based on a suggestion by R. W. Noyes, currently is exploring the feasibility of *doubling* the aperture of the McMath telescope by substituting a 4-m primary and a 6-m heliostat for the existing optics (see W. Livingston, these proceedings): the dry Kitt Peak site is excellent for infrared work; the all-reflecting, unobscured design of the McMath telescope minimizes thermal background; and the cost savings would be substantial compared with an entirely new facility. The unprecedented, unique view of the Sun afforded by a large-aperture IR solar telescope would fuel a major revolution in our understanding of the physical processes that shape the dynamic, chaotically-structured layers above the disarmingly placid visible surface of our nearby star.

Acknowledgements

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Fig. 1 were obtained in conjunction with the RIASS program, under the overall direction of W. Wamsteker, and with the considerable help of "designated observers" at the NASA IUE Observatory (GSFC) and its ESA counterpart at Vilspa. The observations of Fig. 5 were obtained at the Kitt Peak site of NOAO (and NSO), operated by AURA under a cooperative arrangement with the NSF.

References

Ayres, T. R.: 1981, *Astrophys. J.* **244**, 1064.

Ayres, T. R.: 1985, *Astrophys. J. (Letters)* **291**, L7.

Ayres, T. R.: 1990, in J. O. Stenflo (ed.), 'Solar Photosphere: Structure, Convection, and Magnetic Fields', *Proc. IAU Symposium* **138**, 23.

Ayres, T. R.: 1991, in P. Ulmschneider, E. R. Priest, and R. Rosner (eds.), 'Mechanisms of Chromospheric and Coronal Heating', Springer-Verlag, Heidelberg, p. 228.

Ayres, T. R., Fleming, T. A., and Schmitt, J. H. M. M.: 1991, *Astrophys. J. (Letters)* **376**, L45.

Ayres, T. R., Marstad, N. C., and Linsky, J. L.: 1981, *Astrophys. J.* **247**, 545.

Ayres, T. R., *et al.*: 1992, *The RIASS Coronathon: Contemporaneous X-ray and Far-Ultraviolet Measurements of a Review-Panel-Limited Sample of Normal Late-Type Stars*, in preparation.

Burton, R. B.: 1992, *Hidden Binary Systems: the IRAS/IUE Connection*, M. A. Thesis, University of Colorado.

Brown, A., Drake, S. A., Van Steenberg, M., and Linsky, J. L.: 1991, *Astrophys. J.* **373**, 614.

Hartmann, L., Dupree, A. K., and Raymond, J. C.: 1980, *Astrophys. J. (Letters)* **236**, L143.

Heasley, J. N., Ridgway, S. T., Carbon, D. F., Milkey, R. W., and Hall, D. N. B.: 1978, *Astrophys. J.* **219**, 790.

Linsky, J. L., and Haisch, B. M.: 1979, *Astrophys. J.* **229**, L27.

Muchmore, D. O., and Ulmschneider, P.: 1985, *Astron. Astrophys.* **142**, 393.

Parker, E. N.: 1970, *Ann. Rev. Astron. Astrophys.* **8**, 1.

Simon, T., and Drake, S. A.: 1989, *Astrophys. J.* **346**, 303.

Tsuji, T.: 1988, *Astron. Astrophys.* **197**, 185.

Wiedemann, G. R.: 1989, *Development of a Postdispersion System for Astronomical Infrared Observations with Fourier Spectrometers and its Application in the Study of the CO Fundamental Bands in F, G and K Stars*, Ph. D. thesis, University of Munich (MPE Report 214).

Wiedemann, G., and Ayres, T.: 1991, *Astrophys. J.* **366**, 277.