COMospheres and Coronae

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Abstract. I describe three hot topics in cool star research. These range from CO “clouds” in the quiescent low chromosphere of the Sun, to the multi-million degree coronae of solar-type stars in young clusters. I call attention to: (1) the curious separation in X-ray/C IV diagrams between the Hertzsprung-gap giants and their cooler, post helium flash cousins of the “Clump”; (2) the intriguing possibility of flare dominated coronal activity in the youngest solar-type stars; and (3) the remarkable thermal bifurcation of the chromosphere of our middle-aged Sun.

1. Introduction

I will take the happy occasion of the conference honoring Karl-Heinz and Erika to discuss a few topics of current interest (at least to me). The central theme is the highly structured nature of the chromospheres and coronae of F–M stars.

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 in the high altitude layers provides a strong motivation – and an endless source of frustration – for observers and theorists alike. The dazzling array of fine structure on the surface of the Sun challenges the creativity of solar observers. At the same time, it cruelly tantalizes stellar astronomers who can record only the disk average spectra of their subjects. Furthermore, theorists – and their workstations – are more comfortable with spherically symmetric, laterally homogeneous models, rather than the messy reality of the solar chromosphere-corona.

The inhomogeneous character of stellar outer atmospheres is not simply a trivial annoyance that Nature foists upon us. Instead, 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 energization mechanisms requires a concerted effort to dissect the physical properties of the inhomogeneities. That effort necessarily must focus on the ultraviolet and higher energy emissions that form preferentially in the heated gas. At the same time, infrared studies of low excitation species like molecules can shed light on the ambient atmosphere in which the hot structures are rooted. The contrasting – sometimes outwardly conflicting – pictures must be reconciled. Otherwise a complete understanding of the solar chromosphere-corona will elude us. Such a reconciliation also can provide key insights for the far less tractable, but equally important, stellar case.
2. The RIASS Coronathon: X-ray Deficient Giants and Supergiants

Hot (T > 10^6 K) X-ray emitting coronae are found throughout the cool half of the H–R diagram. Our nearby Sun is infested with such “activity”. The Sun’s corona is a driving force in the heliosphere, and a focal point for solar-terrestrial relations. Coronal physics ties together convection, differential rotation, stellar magnetism, wave heating, dynamics, low density plasmas, and more. When one considers the H–R diagram of coronal activity, stellar evolution comes into play as well.

Among solar temperature and cooler stars, coronae usually are blamed on the rotation catalyzed magnetic “Dynamo” (e.g., Vaiana & Rosner 1978). It operates effectively in stars with deep convective envelopes. Possibly a different mechanism – like acoustic heating – functions in the warmer objects with thin convection zones (cf., Simon & Drake 1989 [SD]).

Clues to the nature of coronae can be found in the global structure of the X-ray H–R diagram. Critical boundary regions exist at luminosity class III. Among the moderate mass (∼3M⊙) giants crossing horizontally from the upper Main Sequence, a sharp break in coronal activity occurs just beyond G0 in the Hertzsprung gap (e.g., Schrijver 1993). In the post helium flash Clump at G8–K0, a wide range of X-ray emission levels is present. However, few Clump giants are as X-ray bright as their predecessors in the Hertzprung gap. Redward of about K2 coronae essentially disappear (Linsky & Haisch 1979).

The clear divisions at class III are blurred in the supergiants. These high mass stars (M > 5M⊙) spend most of their short post-MS lives on convoluted “blue loops” in the F/G region. Some, like β Dra (G2 Ib-IIa) and β Cam (G0 Ib), are UV bright and X-ray active. Others, like α Aqr (G2 Ib) and β Aqr (G0 Ib), are UV quiet and X-ray dim. A curious group are the “hybrid chromosphere” K-type bright giants. The prototype is α TrA (K2 IIb-IIIa; Hartmann, Dupree, & Raymond 1980). Such stars exhibit signs of UV and X-ray emission (Brown et al. 1991; Reimers & Schmitt 1992), and even flares (Kashyap et al. 1993). At the same time they harbor strong low excitation winds. The signatures of coronal activity and mass loss usually are mutually exclusive among the lower luminosity giants on the red side of the Linsky-Haisch dividing line.

A few years ago it seemed that coronae might be understood in terms of only a few stellar parameters – rotation, convection zone depth, and surface gravity (cf., Noyes et al. 1984). However, a major stumbling block was the overall poor coverage of stars during the historical X-ray missions. The lack of simultaneous UV spectroscopy – for the few X-ray stars observed – didn’t help either.

ROSAT, and its six month sky survey, changed the situation dramatically. The ROSAT/IUE All Sky Survey (RIASS) coordinated IUE spectroscopy of 128 objects – ranging from planets to Active Galactic Nuclei – during the few day intervals when ROSAT was scanning the appropriate sections of sky. Nearly half of the targets were cool stars. Most of these were from a program called the “Coronathon” (Ayres et al. 1993a).

A striking result is illustrated in Fig. 1. Previously, Ayres, Marstad, & Linsky (1981) found a tight correlation between C IV λ1549 – a key coolant of the subcoronal plasma – and chromospheric Mg II λ2800. Here, however, a diagram pitting coronal X-rays against C IV shows considerable scatter. Separating
Figure 1. Correlation diagram for ROSAT X-ray and IUE C IV fluxes (with apologies to E. B.-V.). The smaller symbols indicate 3σ X-ray upper limits. The dashed line is a 3/2 power law based on the MS G/K stars.
the stars by luminosity as in Fig. 2 clarifies the situation. One finds that the jumble of the previous figure is in fact a bifurcation. The G/K dwarf stars and the Clump giants lie on one activity track. The Hertzsprung-gap F/G0 giants and luminous G/K supergiants lie on a second – X-ray depressed – locus. The bifurcation is an extension of the “X-ray deficiency boundary” identified by SD for early-F dwarfs and Hertzsprung-gap giants. Why it exists is a mystery. However, a possible unifying theme has surfaced recently.

An HST-inspired reexamination of archival IUE echelle spectra of Capella (G8 III + G0 III) revealed a striking variability of the blue peak of the H I Lyα emission (Ayres et al. 1993b). The most natural explanation invokes a high speed warm wind from the G0 secondary, a Hertzsprung-gap star. The mass loss rate is not large, but the implied magnetospheric braking timescales are short, consistent with Gray’s \( v \sin i \) break (e.g., Gray 1991; see also SD).

A similar study of the hybrid star α TrA has been carried out by myself and V. Kashyap (1993). We found that the pronounced asymmetry of its H I emission profile cannot be produced exclusively by ISM absorption plus low velocity (−80 km s\(^{-1}\)) circumstellar absorption (as seen in Mg II \( \lambda 2800 \)). Like Capella, a straightforward way to explain the asymmetry invokes a high velocity (−400 km s\(^{-1}\)) coronal outflow. Such a wind would be an important drain of energy and angular momentum.

A common theme, then, among the stars of the lower activity branch is the existence of some type of significant mass loss. Usually it is most evident as a low speed, low excitation wind. In other cases, a high speed coronal outflow might accompany – or replace – the cool wind.

HUBBLE has added an unexpected new slant to these issues.

3. The FUV Emissions of Solar-Type Stars in Young Clusters

HST and its two main ultraviolet spectrographs (FOS & GHRS) have opened new opportunities in the exploration of stellar outer atmospheres. The FOS, in particular, is hundreds of times more sensitive than the venerable IUE, and its reach is correspondingly deeper.

I, and my collaborators, have been using the FOS to study faint UVE spectra in young Galactic clusters. Our intent is to explore the early evolution of the Dynamo, and associated subcoronal activity.

Fig. 3 compares coadded spectra of the youngest stars (Pleiades and α Per clusters: age \( \approx 50–70 \) Myr) and the older stars (Hyades cluster: age \( \approx 600 \) Myr). Note the high levels of scattered light from the G130H disperser. Fig. 4 correlates the HST/FOS C IV fluxes vs. ROSAT PSPC detections (X-ray fluxes for the α Perseids are not yet available; I assumed \( \log L_X = 30 \pm 0.3 \), the “saturation” level indicated in the Pleiades). The points in the lefthand panel are from the RASS program described previously. Here, the power law connecting just the F9–G2 stars has a slope of 2 (and is repeated in the HST panel).

The young cluster members lie at the upper bounds of X-ray and C IV emission. Already by Pleiades age, however, there is a wide dispersion in activity among the ostensibly coeval stars. The dichotomy might be a relic of the pre-MS evolution of the stellar spins. Alternatively, it might arise later through
Figure 2. – Same as Fig. 1, but separated according to luminosity class. The dashed line in each panel is a 3/2 power law based on the MS G/K stars. The Hertzsprung-gap giants and the G/K supergiants (including the "hybrid" K bright giants) fall on an X-ray deficient track. The low activity red giants show evidence for a "basal" flux in C IV, but not in X-rays.
Figure 3. — *FOS G130H* spectra of solar-type stars in young clusters. The upper trace is a combined spectrum of three Pleiads and one α Per star; the lower is of five Hyads. The spectra are in cnts/s, scaled to V = 0. The hatched areas indicate the large scattered light levels. The H I and O I emissions mostly are geocoronal.

the action of coronally regulated angular momentum loss (see, e.g., papers from Session 2 of the recent Cool Stars 8 Workshop).

Perhaps more significantly, one of the Pleiads – H II 314 – flared in C IV during the final of its three orbits of HST observations (Ayres et al. 1994). The two α Per stars showed signs of short term fluctuations as well. Fig. 5 depicts the H II 314 flare. The scattered light (mostly mid-UV continuum radiation) also exhibits variability possibly related to flare heating of the lower atmosphere.

Previous ROSAT pointings on that region had found factor of two slow variations in the X-ray flux of H II 314 (Caillault et al. 1993). Based on these limited, but provocative, results I and my collaborators believe that flares fuel the high activity of young fast rotating G dwarfs.

If so, flare associated mass loss (analogous to Coronal Mass Ejections on the Sun) provides a natural magnetospheric spin-down mechanism. A high powered brake is required to explain the dramatic subsiding of coronal activity from Pleiades age to Hyades age (e.g., Stauffer 1987). If flaring plays a key role in the cluster dwarfs, then it likely is important for other hyperactive stars as well. Simon (1984) already has shown that flaring at high activity levels provides a natural explanation for the nonlinear power laws in flux-flux diagrams.

HUBBLE has provided a tantalizing glimpse of the possible early coronal history of the young Sun. However, our neighbor star – at the zenith of stellar activity – recently has revealed a few surprises of its own.
4. Off-Limb Emission of the CO Fundamental Bands

A striking aspect of the inhomogeneous outer atmosphere of the Sun are condensations of molecular gas within the boundaries of the hot chromosphere. The “cool clouds” have been nicknamed the COrmosphere by G. Wiedemann. It manifests itself most clearly in the anomalous limb darkening of the strong CO $\Delta v = 1$ bands near 4.6 $\mu$m, first recognized by Noyes & Hall (1972). The existence of the molecular gas in the otherwise hot chromosphere can be explained in terms of a radiative cooling instability, driven by optically thin emission in the CO fundamental bands themselves. The instability operates when the local mechanical heating is weak (Ayres 1981).

The “thermal bifurcation” mechanism is an elaboration of the key role of CO surface cooling, originally discussed by Tsuji (1964) and Johnson (1973) in the context of red giants. Sophisticated NLTE blanketed models, in radiative equilibrium (Anderson 1989) and with prescribed mechanical heating laws (Anderson & Athay 1989), confirm the qualitative principles of the model. The most important is the abrupt transition from COrmosphere to chromosphere proper at a critical level of input mechanical heating. The mechanism is one aspect of “molecular cooling catastrophes” (e.g., Stencil 1987). These operate in a diversity of cosmic settings, from the fueling of starbursts in distant galaxies (Scoville & Soifer 1990) to the formation of silicate grains in the extended envelopes and winds of nearby red giants (e.g., Muchmore, Nuth, & Stencil 1987).

The very existence of the COrmosphere has been controversial. The primary reason is that the cool material cannot easily be traced in any diagnostic other...
Figure 5. — Time series of $C$ IV fluxes of H II 314. The G130H observation was over three HST orbits, each consisting of seven 4.2 minute readouts. The $C$ IV fluxes are shown in the lower panel. The decay of a large flare can be seen at the beginning of the third orbit; a smaller burst in the middle of the second. The upper panel shows the behavior of the scattered light level.
than CO. Few species have the required sensitivity to cool temperatures, and strong enough lines to thermalize in the middle chromosphere. The 4.6 \( \mu \)m CO bands themselves are a challenge to reach, even in the Sun, owing to limitations of the existing instrumentation. Recently, however, the Main spectrograph of the NSO McMath telescope has been fitted with a large IR grating (recycled from the defunct horizontal IRSG).

Last March (1993), W. Livingston conducted tests of the new setup, using a single element InSb detector. He obtained several drift scans across the solar diameter at about 2\( '' \) resolution, in the IR continuum and in the core of a strong CO \( \Delta v = 1 \) transition. He also took a series of short spectral scans very close to, and above, the limb. The latter were done under conditions of excellent seeing. The IR continuum fades very rapidly above the apparent limb. The strong CO lines, however, revert from pure absorption to emission as the underlying continuum falls away. Furthermore, the CO emissions persist to surprisingly large distances – nearly 1\( '' \) – above the IR limb, corresponding to altitudes within the middle chromosphere itself (\( h \approx 900 – 1100 \) km). Such behavior is completely inconsistent with the best available single component models of the solar chromosphere (e.g., Fontenla, Avrett, & Loeser 1993).

Solanki, Livingston, & Ayres (1993) have reported the main results. We devised a model having cool temperatures (\( T = 3500 \) K) in the low chromosphere, but with a sharp rise to normal chromospheric values at a critical altitude. Such models simulate a cool COmosphere lying under a hot chromospheric “canopy” formed by the vertical spreading – and eventual merging – of the network magnetic fields. Fig. 6 illustrates a typical model and the resulting limb curves.

Our simulations suggest that as much as 50–85\% of the surface is covered by the cool COmosphere, with a range in canopy altitudes of about 900–1100 km. Our conclusions must be verified by direct imaging experiments. However, the drift scans taken by Livingston show no evidence for the ultracold “dark points” required in the alternative scenario in which the COmosphere is confined to 15\% or less of the surface (see, e.g., Ayres 1991).

Livingston’s work represents an important validation of the thermal bifurcation scenario. Ironically, the mechanism is relatively feable in early-G stars like the Sun owing to the elevated radiative heating in the outer atmosphere. The COmosphere/chromosphere dichotomy should be more pronounced in low gravity cool giants. However, IR studies of the relatively faint stars must await further technical advances. Nevertheless, CO 4.6 \( \mu \)m observations of the red giants, coupled with mid- and far-UV spectroscopy, should provide a strong spectral lever to pry out additional insight concerning stellar surface inhomogeneities.

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Figure 6. – Thermal model (upper panel) and off-limb CO and IR continuum behavior (lower panel: note scale change at 0") (© Astronomical Society of the Pacific • Provided by the NASA Astrophysics Data System). The “CO-mosphere” is the extended zone with $T = 3500$ K between the classical “$T_{\text{min}}$” at 500 km and the hot chromospheric “canopy” at 1100 km. In the lower panel the dots are predicted continuum intensities (normalized to disk center value). The crosses are simulated core intensities of the strong 2–1 R6 CO transition (also normalized to the disk center continuum intensity). The CO core shows strong absorption on the disk, but (relative) emission off-limb. The CO emission extends nearly 1" beyond the continuum half power point (corresponding to 700 km $\approx$ ten pressure scale heights). In conventional chromospheric models, the CO emission extends only 0.25" above the limb, contrary to the recent observations.
References

Ayers, T. R., & Kashyap, V. 1993, in Cool Stars 8 Workshop, in press
Noyes, R. W., & Hall, D. N. B. 1972, BAAS, 4, 389
Scoville, N., & Soifer, B. T. 1990, in Massive Stars and Starbursts, Proceedings of STScI Workshop, (Baltimore: STScI)
Chapter VI

Cepheid Variables